

Martin Johansen

Controlling pipeline global buckling behavior by installing prebent sections

Master's thesis in Subsea Technology

Supervisor: Svein Sævik

January 2020

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

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MASTER THESIS WORK SPRING 2020

for

Stud. Tech. Martin Johansen

Controlling pipeline global buckling behaviour by installing prebent sections

Kontrollert global knekking av rørledninger med bruk av forbøyde rørseksjoner

For pipelines that are left exposed on the seabed, global buckling may occur due the axial compressive force developed as a result of the elevated pressure and temperature experienced during the operating condition. In order to design against such behaviour it is important to absorb the axial displacement potential from the temperature/pressure elongation effect by means of controlled lateral global buckling at regular intervals. This requires that lateral imperfections are introduced in the pipeline at the locations where buckling is wanted. For flat seabed conditions, one way of obtaining this is to install so-called sleepers (rock dumps or tube sections) prior to installation providing imperfections in the vertical plane. An alternative to this is to introduce pre-bent sections by plastic deformation of pipe sections in the pipeline at the installation vessel. The major objective of this thesis is to investigate the feasibility of introducing such imperfections with respect to installation and operation during flat seabed conditions. The work is to be carried out as a continuation of the project work carried out during Spring 2020 and includes the following items:

1. Literature study related to methods for global response analysis of pipelines undergoing installation and operation load scenarios including relevant standards and recommended practices.
2. Define basis for case studies including mechanical properties, installation vessel characteristics, operating conditions, route geometry and soil conditions
3. Model the pipeline installation process in SIMLA including the pre-bent section effect (initial strain) for the different cases.
4. Perform parameter studies with respect to imperfection interval, length, curvature, length model/torsion constraint, friction coefficient, installation tension, water depth etc.
5. Demonstrate that the configurations established on the seabed works as intended.
6. Conclusions and recommendations for further work.

The work scope may prove to be larger than initially anticipated. Subject to approval from the supervisors, topics may be deleted from the list above or reduced in extent.



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Abstract

Offshore pipe laying operations are quite common in the offshore industry. These operations are getting more and more complex due to new challenges that demand advanced solutions. The pipe-laying method studied in this Thesis is J-lay. This method uses a large laying vessel to lay the pipeline at the seabed. The pipeline has a J- shape when it hangs from the vessel during installation. For pipelines that are left exposed on the seabed, global buckling may occur due to the axial compressive force developed as a result of the elevated pressure and temperature experienced during the operating condition. In order to design against such behavior, the residual curvature method is introduced. Residual curvature means that a turning point with a particular curvature is placed along the pipeline; this curved section is produced at the vessel by deforming the pipe. This section is called imperfection. The goals of this Thesis is to prove that it is possible controlling the global buckling by installing the pipeline with residual curvature and recommend a configuration of the laying scenario. The pipeline leaves the vessel with a certain departure angle. This departure angle depends on the horizontal tension, water depth, and submerged weight. The pipeline is produced at the vessel as the pipe is deployed from the vessel and laid at the seabed.

SIMLA is used to analyze the installation and operation sequence. SIMLA is a program created just for this purpose. The program is run by using three input files. The first file creates a static equilibrium configuration between the vessel, seabed, and pipeline. The second file simulates the installation sequence when laying the pipe, and the last file simulates the operational sequence. By running these files in order, it is possible to find the axial forces and moments that are used to check if the analyzes are within the load criteria. The analyzes need to pass one installation load criteria and one operational load criterion to be valid. The offshore standard OS-F101 defines these two criteria. A MATLAB script that takes these load criteria into account is used to check if both are fulfilled. The result of one analyzes with a specific configuration of parameters is called one case. In order to find the optimal case, a parameter study with a series of different configurations is run by using a program called GITBASH.

Imperfection lengths of 2m, 4m, 10m, 30m, and 40m are analyzed with a departure angle of 70, 75, and 80 degrees. After 205 different analyzes, an imperfection length of 40m is proven to be the most robust length. Robust means that this length often leads to valid results. It is essential that the imperfection rotate and buckle in a controlled manner.

The imperfection of 40m is proven to be rotating and lies on the seabed when the installation sequence ends. It is also proven that the imperfection buckles in a controlled manner during the operational sequence. The controlled buckling and the rotation happens every time the analyses converge, and the development in axial force is stable. The buckling sequence happens in a controlled manner without any instability when the operating temperature and pressure are applied. The buckling never happens during the installation sequence, only the rotation of the imperfection. The movement of the vessel during the installation sequence is proven to be unrealistic. The steering algorithm of the installation sequence happens to have strict tolerances concerning the theoretical laying route at the seabed. Some of the cases do not converge because of this algorithm. This because the pipe tries to hit the center of the laying route as the curved

section makes contact with the seabed. It is proven that the torsion spring needs to be quite slack for some of the cases to converge. Including wave load, even when there is no wave, has a dampening effect on the axial force due to contribution from drag. Imperfection lengths of 2 and 4m have a high and unstable development in the axial force, which is undesirable.

In summary, these findings prove that it is safe to lay a pipeline at 380m water depth with an imperfection length of 40m with departure 70, 75, or 80 degrees. The main goal of controlling global buckling by installing prebent sections is achieved.

Preface

This thesis is the leading finishing report that is a part of my master's in Subsea Technology at the Department of Marine Technology at Norwegian University of Science and Technology in Trondheim. The problem described in this Thesis is given by Equinor. The purpose of this Thesis is to prove that the overall global buckling can be controlled at the initial phase of operation by introducing imperfections during the installation sequence.

Acknowledgment

I would like to thank some people that have helped and guided me through this thesis

First of all, I want to thank my professor Svein Sævik for the possibility of writing this Thesis under his supervision. I appreciate the guidance and advice during the process of completing this Thesis. The guidance has been very beneficial for the result presented in this Thesis. I would also like to thank Eirik Levold, who is working for Equinor. I appreciate the opportunity to write about the Skuld project, which is relevant and exciting for my education. Writing a Thesis for the leading company in Norway concerning pipe laying has always been on the top of my list.

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Norwegian University of Science and Technology

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Martin Johansen

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Abbreviations and nomenclature

Abbreviations

FEM	Finite Element Method
TDP	Touch Down Point
TSRP	Torsion Spring Rotation Parameter

Nomenclature

α	Departure angle
α_C	Flow stress parameter
α_U	Material strength factor
α_{fab}	Maximum fabrication factor
β	Combined loading factor
\dot{U}_b	Flow velocity
\dot{U}	Flow acceleration
γ_A	Accidental load factor
γ_C	Condition Load Effect factor
γ_E	Environmental load factor
γ_F	Load Effect factor
γ_m	Material resistance factor
γ_{SC}	Safety class resistance factor
ϕ	Phase angle
ρ	Density Seawater
$\varphi\omega$	Wave direction angle

A	Reference area
C_D	Drag coefficient
C_m	Inertia coefficient
d	Water depth
$f_{u,temp}$	De-rating factor tensile strength
$f_{y,temp}$	De-rating factor yield stress
f_o	Ovality of Pipe
g	Gravity
k	Wave number
M_A	Accidental bending moment
M_E	Environmental bending moment
M_I	Interference bending moment
M_p	Plastic moment capacity
M_{Sd}	Design moment
P_c	Resistance for external pressure
P_e	External pressure
P_i	Characteristic internal pressure
P_{min}	Minimum internal pressure
R_{min}	Minimum bending radius
s	Curvilinear length
S_A	Accidental axial force
S_E	Environmental axial force
S_F	Effective axial force
S_I	Interference axial force
S_p	Plastic tension capacity
S_{Sd}	Design effective axial force
T_0	Effective horizontal tension

U_b	Velocity of a moving body
ν	Poisson ratio
w_s	Submerged mass
D	Diameter pipe
H	Wave height
SMTS	Tensile strength
SMYS	Yield Stress
t	Thickness pipe

Introduction

This master Thesis study pipelines that experience uncontrolled local buckling when operating. Subsea pipelines are installed on the seabed by using pipe laying vessels. During this marine operation, challenges due to plasticity are experienced. This leads to buckling of the pipe when operating. The overall global buckling has to be controlled to verify that the pipe can withstand the axial-forces and moments.

Controlling the global buckling can be solved by creating planned local imperfections along the pipeline with a constant distance between each other. Imperfection sections are where the pipe is curved. The imperfections are deformed to a specific curvature before the pipe is deployed from the vessel. To prove that this work, SIMLA, which is a program to simulate different pipe laying scenarios, is used. It is also necessary to check if the pipe buckles at each curved section when the operating temperature and pressure are applied. The analysis needs to verify that the pipe buckles and fulfill the load controlled condition criteria, described in the offshore standard OS-F101.

1.1 Background

Pipe laying is an expensive operation. It is therefore needed to analyze every sequence to make sure that the operation goes as planned. The behavior of the pipe after installation and when it starts to operate is essential to analyze. The main goal in the oil industry is to make offshore operations cheaper and more effective. By planning operations in detail and know what to expect, this goal is reachable.

When laying a pipeline on the seabed, it is crucial to predict how the pipe will behave when interacting with the seabed. The seabed conditions along the laying route can vary and affect the behavior of the pipe. It is, therefore, an advantage to have a flat seabed which is usually not the case.

To deal with this challenge, rocks are dumped along the route by a rock dumping vessel to flatten the seabed. This to elevate the seabed so the pipe can be put down without experience large deformations due to large bending moment as a result of the free span. This rock dumping operation is expensive and takes time to plan and execute. By controlling the laying sequence and understand how the pipe behaves during laying and operating, many problems can be avoided. Adding imperfections along the pipe is a solution called the Residual curvature method and lets

us being able to control the operation concerning the environment and underwater topography. This can lead to more time effective operations.

1.2 Scope

The purpose of this Thesis is to prove that the overall global buckling can be controlled at the initial phase of operation by introducing imperfections during the installation sequence. The economic perspective of the problem is not discussed in this Thesis.

Scope of this Thesis:

- Literature study related to methods for global response analysis of pipelines undergoing installation and operation load scenarios, including relevant standards and recommended practices.
- Define the basis for case studies including mechanical properties, installation vessel characteristics, operating conditions, route geometry, and soil conditions
- Model the pipeline installation process in SIMLA, including the pre-bent section effect (initial strain) for the different cases.
- Perform parameter studies with respect to imperfection interval, length, curvature, torsion constraint, rotation constraint, and friction coefficient
- Demonstrate that the configurations established on the seabed work as intended.
- Conclusions and recommendations for further work.

1.3 Content of thesis

The primary purpose of this subsection is to introduce the reader to the structure of this Thesis.

Introduction

Chapter 1 gives an introduction to the problem and explains the background and the reason why this Thesis is written. The main goal is to give a general understanding and provide relevant information before going into detail concerning how the problem is solved.

Literature review

Chapter 2 states what is already known regarding the problem presented in the introduction. Results from different studies, methods that are used, and standards that need to be followed are explained in this chapter.

Theory

Chapter 3 explain relevant theories and the mathematics behind SIMLA that perform the analysis. This chapter also explains the parameters used in relevant equations for the load control criteria from the standard.

Laying scenario

Chapter 4 defines the laying scenario with the environmental and pipe data provided by Equinor. Capacities of the laying vessel is also described.

Modeling and analysis

Chapter 5 explain how the pipeline model is created by using finite element method within SIMLA and how to run the analysis. The function and order of the different input files for the analysis to be run is described.

The parameter study is also explained in detail. The parameter study is divided into six different parts based on which parameters that change. A detailed explanation of the analysis goal and an overview of the changing parameters for every part are listed.

Result and discussion

Chapter 6 is divided into the same parts as in the parameter study in Chapter 5. First, the table is explained; then, the results are listed before the discussion.

Conclusion

Chapter 7 has a short conclusion that defines the most optimal case for laying the pipeline and other findings. It also includes recommendations for further work.

Literature Review

2.1 Pipe laying methods

Pipelines are installed all over the world every day. This is getting done by vessels that are constructed just for this purpose. When installing the pipeline at the seabed, different methods are used. These depend on the water depth, the diameter of the pipeline, and the pipeline's weight.

The methods that are used:

- S-lay method
- J-lay method
- Reel lay method
- Tow installation

S-lay is mostly used in shallow waters. The name comes from the S-shape the catenary gets when installing the pipe on the seabed. The catenary is the overall configuration of the whole vessel and pipe setup. The J-lay and Reel lay methods are used at intermediate to deep waters. The Tow installation is used at any depth. This installation method is divided into four categories for which depth the installation is towed at. [Rigzone, 2014]

J-Lay

The method used in this thesis is J-lay. The reason for the name is because of the J-shape of the catenary. The departure angle of this operation depends on the horizontal tension, water depth, and submerged weight. Two methods are used to feed the pipe while laying.

- Feed from storage reel or under deck carousel
- Feed from storage deck

Reeling is done by installing the pipe on a large storage reel while the vessel is mobilizing at the port. This reeling process bends the pipe around the storage reel that leads to plastic deformations. The limitations of this method are that the diameter of the pipe cannot exceed 18 inches. The pipe needs to be straightened back due to this plastic deformation before the pipe leaves the vessel. This is done by a straightener mounted in the tower at the back of the vessel. J-lay with storage reel is illustrated in Figure 2.1

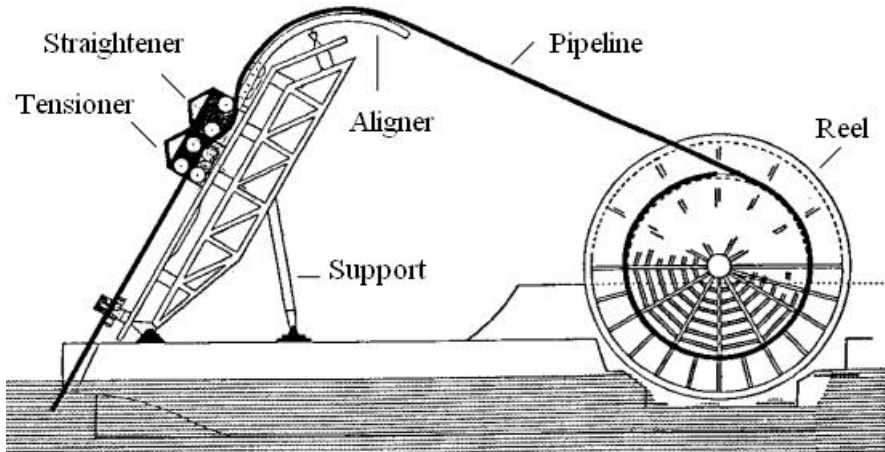


Figure 2.1: Storage Reel

The storage deck method is done by producing the pipeline at the vessel. The production is done by welding pipe sections together in a welding station before laying them. This station is located in the tower. The advantage of this method is that the pipe does not get plastic deformed due to bending over a storage reel. It is required to weld the sections together almost vertically in the tower due to the large departure angle. The result of this is a high tower. This method is suitable for larger diameters. The disadvantage is that this method takes more time than the storage reel due to the production on board. J-lay with storage deck is illustrated in Figure 2.2 [Marine, 2014]

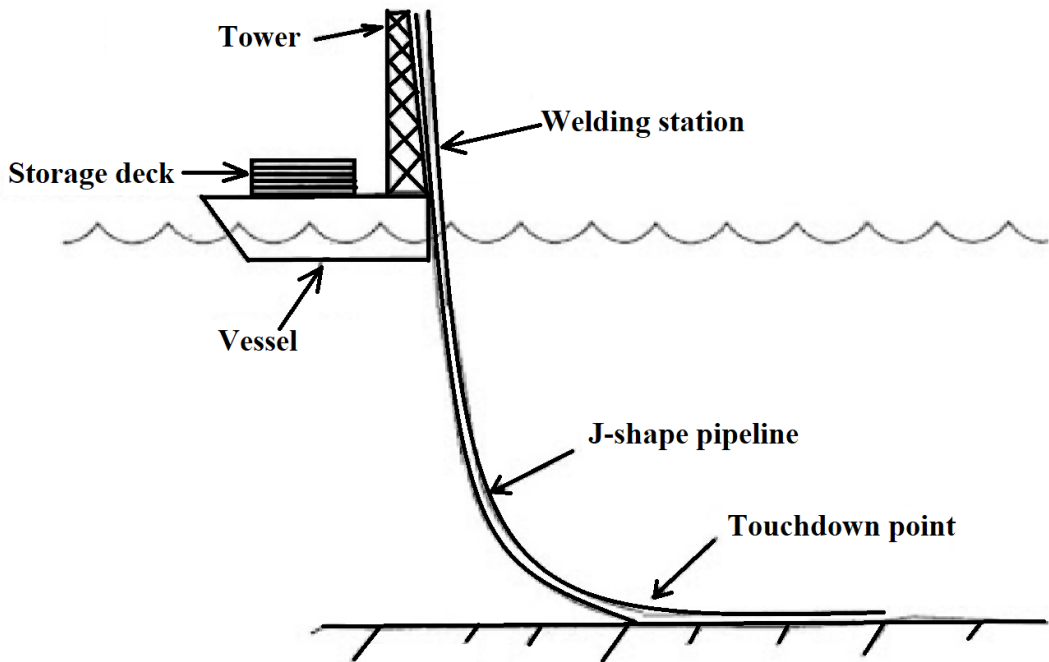


Figure 2.2: Storage deck

2.2 Residual Curvature

Residual curvature is a section of the pipe that is curved due to plastic deformations. This happens naturally during J-lay operations when storage reels are used. These operations use a straightener that deforms the pipe back to its original straight shape. The straightener overcomes the residual curvature that is created by storing the pipe on the storage reel. If residual curvature sections are wanted, the straightener settings need to be changed at the wanted sections. The result of this is that the pipe will leave the vessel as a straight pipe and with wanted curved sections also called imperfections. [ASME, 1992]

For J-lay operations not using storage reel, the pipe is originally straight because straight pipe sections have been welded together almost vertically in the tower. To achieve a residual curvature section, the straightener has to plastic deform the pipe. The reason for this is that the residual curvature does not happen by itself due to no storage reel. Pipeline configuration with residual curvature is illustrated in Figure 2.3. [Ibrahim, 2017]

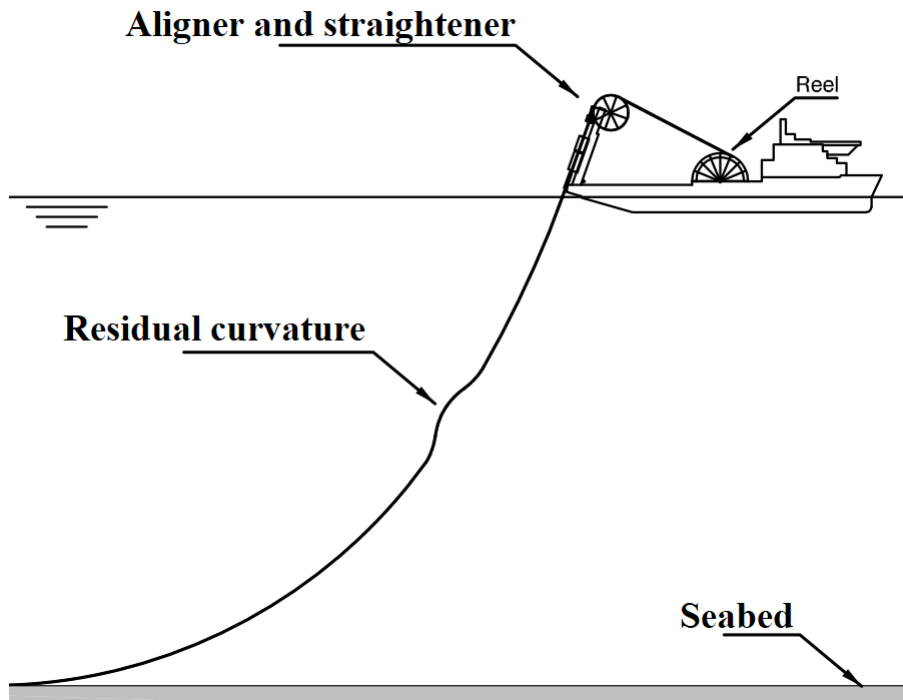


Figure 2.3: Pipeline configuration with residual curvature

2.3 Global buckling of pipelines

Installed pipelines that operate while laying on the seafloor experience, increasing pressure, and temperature. This because of the temperature and pressure of the content inside the pipe. This increased pressure and temperature will try to expand the pipe. If an external force is applied to the pipe, buckling may occur when the axial or compression forces are at a certain level. These forces can, for example, be the result of interacting with the seabed. The global buckling phenomena is hard to control because of the uncertainty of how the pipe interacts with the seabed.

A recommended practice is used to check and ensure that the criteria and methodology are correct concerning the requirements regarding global buckling. The requirements are defined in the offshore standard OS-F101. A more detailed description of the standard and the recommended practice is described in Subsection 2.6 and 2.7. The recommended practice describes the design procedure that is divided into three steps.

1. Global buckling assessment
2. Pipe integrity check
3. Mitigation measure check

Step 1: Global Buckling Assessment

This assessment is to determine the susceptibility of global buckling. The result is to set criteria for local buckling. Three scenarios are discussed:

- No buckling
- Maybe buckling
- Buckling

Since we want the pipe to buckle by adding imperfections while laying, the obvious result of this assessment is that buckling will occur. The determination of these criteria, if the case is not that clear, is described in detail in the recommended practice.

Step 2: Pipe integrity check

This check is performed to ensure that the integrity of the pipe is obtained. The failure modes are local buckling, fatigue, and fracture. This step is divided into the same three scenarios as for the global buckling assessment. To get satisfying integrity check the following have to be fulfilled.

- Combined moment check for stress-strain curve based on the characteristic yield strength f_y and characteristic tensile strength f_u
- Best estimate pipe-soil resistance values
- Best estimate trawl loads
- Determine the condition load effect factor γ_c
- Strain criterion for the worst case

Step 3: Mitigation measure check

This step is to ensure that the pipeline will buckle at all the imperfection points and not only at one location. The way to ensure that this happens is to check if the effective axial force is higher than the global axial capacity when the next imperfection is reached. If the value is above, the imperfection will have enough axial initiation force for the buckle to be triggered. If it is below, the pipe will not buckle at the second point, and the first buckle will be taking the whole load. This is critical and can lead to fracture at the first buckle. [DNVGL, 2007]

2.4 Residual Curvature Method

Marine contractors have conducted several analyses regarding the residual curvature method. Their results for RCM for Lateral Buckling of Deepwater Flowlines are listed below. These results can be useful to have in mind when discussing the results of the analysis in Chapter 6. They can also be compared to some of the results in Chapter 6.

- The RCM feature is pulled straight at the top of the catenary, but re-appears in the sag-bend and on the seabed due to elastic recovery when the tension reduces [Cooper et al., 2017]

-
- A 40m long RC section with 0.15% residual strain provides a good balance between limited reverse bending loads in the upper part of the catenary and good buckle initiation reliability in operation [Cooper et al., 2017]
 - The method is equally suitable for single-wall flowlines and PIP flowlines Residual Curvature Method for Lateral Buckling of Deepwater Flowlines [Cooper et al., 2017]
 - Relatively low buckle initiation forces are confirmed, which greatly simplifies overall system design and provides flexibility in EPCI schedule and field layout [Cooper et al., 2017]
 - Relatively low peak strains are expected in the buckles and these peak strains are not very sensitive to levels of pipe-soil friction [Cooper et al., 2017]
 - It is likely that the RCM feature will rotate (twist) by more than the “ideal” 90° leading to the potential for an “inverted” RCM feature on the seabed. The in-place response of this inverted RCM feature is found to be favorable, with similar or lower peak strains to the “ideal” case. [Cooper et al., 2017]

2.5 Behaviour of offshore pipelines subjected to residual curvature during laying

Kjell Holthe and Svein Remseth discovered in 1992 that for all pipes in their analysis, the plastic deformations do not affect the configuration of the pipe on the sea bed. They analyzed if the stinger during the S-lay method resulted in plastic deformations on the pipe while laying. This means that the pipe leaves the stinger at the vessel with a residual curvature. Their main focus was to investigate the twisting of the pipe when the residual curvature has to be overcome before laying the pipe. They were able to demonstrate that plastic deformations over the stinger are likely to cause the pipeline to roll in the underbend. [ASME, 1992]

2.6 DNVGL-OS-F101

The overall standard when it comes to submarine pipeline systems is DNVGL-OS-F101. The standard is meant to provide guidance and requirements to the engineer. The focus is the structural integrity of the whole pipeline, and the standard gives guidance and requirements to the following:

- Concept development
- Design
- Construction
- Operation
- Abandonment of pipeline systems

In this Thesis, the main focus will be on guidance and requirements concerning design. The relevant design criteria are to determine that the load controlled condition is within all capacities for all cross-sections during laying. [DNVGL, 2010]

2.7 DNVGL-RP-F110

DNVGL-RP-F110 Global buckling of submarine pipelines is a recommended practice from DNVGL. This recommended practice is meant as a guide for the engineer to ensure that the design methodology and criteria concerning global buckling are followed as described in the standard OS-F101.

The objective of this document is to provide procedures and criteria to fulfill the functional requirements to global buckling and make sure that the pipeline will buckle in a controlled and safe manner. As the main object of this report is to control the global buckling behavior of the pipeline by applying imperfections on the pipe, it is highly important to follow this document. The document divides the design scenarios into three:

1. Exposed pipeline on even seabed
2. Exposed pipeline on the un-even seabed
3. Buried pipeline

It will only be necessary to look at scenario 1 in this Thesis . [DNVGL, 2007]

Theory

This chapter is describing the theory behind the methods and results that are presented in this thesis. The program that is used for running the analysis is called SIMLA. It is, therefore, also essential to understand the theory and mathematical principles behind this program. Basic knowledge regarding pipe laying is also explained.

3.1 Catenary equations

Some factors determine the configuration of the pipeline from the vessel, which is also called the catenary. These equations are relevant when creating a static equilibrium between the vessel, pipeline, and seabed. Overview of the configuration is illustrated in Figure 3.1.

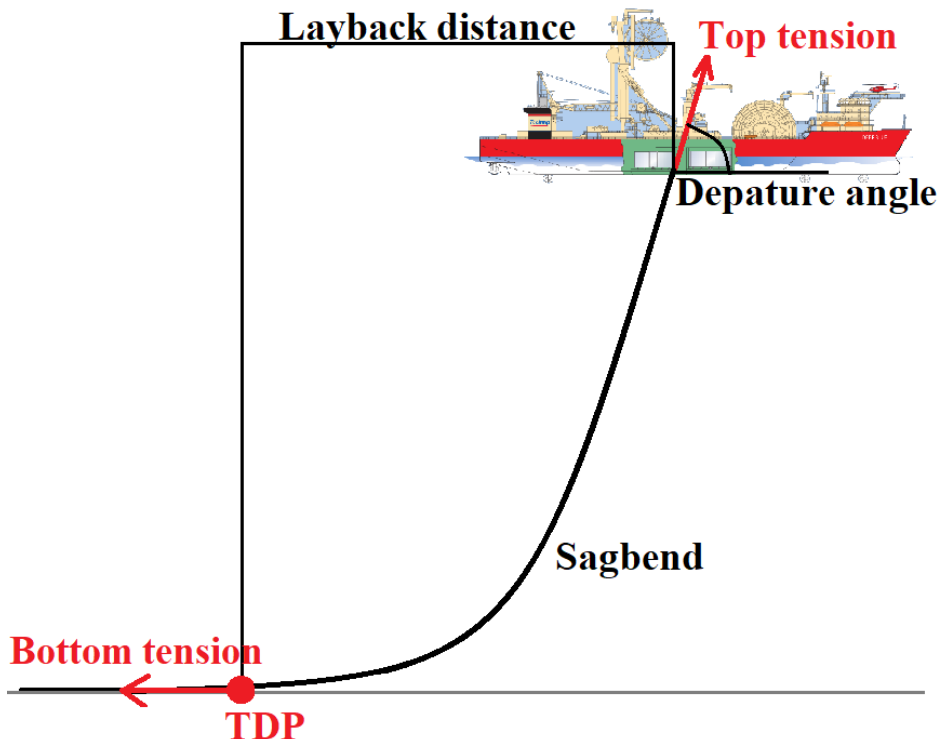


Figure 3.1: Pipe lay configuration

Tension

The top tension is defined as the bottom tension plus the submerged weight multiplied by the depth. This value is the most important when the catenary equilibrium shall be defined. Sometimes laying the pipe with constant tension is preferred. The bottom tension is also defined as the effective horizontal bottom tension described by Equation 3.1.

$$T_0 = \frac{w_s d}{\tan^2 \alpha} (1 + \sqrt{1 + \tan^2 \alpha}) \quad (3.1)$$

Where w_s is submerged mass, d is water depth, α is the departure angle.

Sagbend

Sagbend is the part when the pipeline has a curved downward shape. For flexible pipes with buoyancy sections, the pipeline has a different upward shape called hogbend. This shape is not relevant to rigid J-lay operations, but is the opposite of sagbend.

The curve of the sagbend is determined by the top tension, submerged weight of the pipe, and the material stiffness. If the top tension is increased, the sagbend curvature decreases. If the top tension is too low, the pipe can start to buckle. The curvature at the touch down point is defined by Equation 3.2 [Science, 2005]

$$\frac{1}{R_{min}} = \frac{w_s}{T_0} \quad (3.2)$$

where R_{min} is the minimum bending radius

Touch down point

The Touch Down Point (TDP) is the location where the pipeline makes contact with the seabed. This location is essential when it comes to knowing the status of the laying operation because it is used as a reference point when calculating the total layback distance.

Curvilinear length

The curvilinear length is the distance between the TDP and the sea along a section of the catenary

$$s = \sqrt{d^2 + \frac{2dT_0}{w_s}} \quad (3.3)$$

Departure Angle

Departure angle is the laying angle between the still water line of the pipeline and the vessel. The angle is determined by the angle of the tower at the vessel. Equation 3.4 determines the departure angle.

$$\alpha = \tan^{-1} \frac{w_s s}{T_0} \quad (3.4)$$

Layback

Layback is the distance from the TDP to the reference point on the vessel. The reference point

is usually set to where the pipe leaves the vessel. This distance is essential when it comes to having control while installing. Equation 3.5 determines the layback distance x [Sævik, 2017a].

$$x = \frac{T_0}{w_s} \ln \left[1 + \frac{w_s d}{T_0} + \sqrt{\left(1 + \frac{w_s d}{T_0} \right)^2 - 1} \right] \quad (3.5)$$

Figure 3.2 show an overview of the catenary equations.

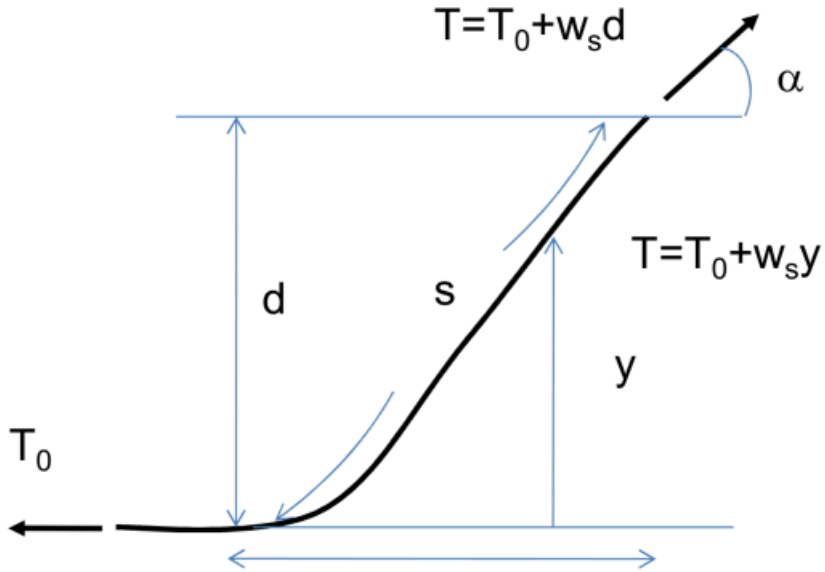


Figure 3.2: Illustration catenary equations

3.2 Load controlled condition

The load controlled condition is defined in the standard OS-F101. Equation 3.6 is the governing equation when the pipe members are subjected to bending moment, effective axial force, and external overpressure [DNVGL, 2010], in this case, when the pipeline is installed. Equation 3.7 is the governing equation when the pipe is subjected to internal overpressure. In this case, Equation 3.7 is used when the pipeline is operating. Both equations need to be satisfied at all cross-sections along the pipeline.

Load control condition installation

External over pressure

$$\left\{ \gamma_m * \gamma_{SC} * \frac{|M_{Sd}|}{\alpha_c * M_p} + \left\{ \frac{\gamma_m * \gamma_{SC} * S_{Sd}}{\alpha_c * S_p} \right\}^2 \right\}^2 + \left(\gamma_m * \gamma_{SC} * \frac{P_e - P_{min}}{P_c} \right)^2 \leq 1 \quad (3.6)$$

Used when $15 \leq \frac{D}{t} \leq 45$, $P_i < P_e$, $\frac{|S_{Sd}|}{S_p} < 0.4$

Load control condition operation

Internal over pressure

$$\left\{ \gamma_m * \gamma_{SC} * \frac{|M_{Sd}|}{\alpha_c * M_p} + \left\{ \frac{\gamma_m * \gamma_{SC} * S_{Sd}}{\alpha_c * S_p} \right\}^2 \right\}^2 + \left(\alpha_p * \frac{P_i - P_e}{\alpha_c * P_b} \right)^2 \leq 1 \quad (3.7)$$

Used when $15 \leq \frac{D}{t} \leq 45$, $P_i > P_e$, $\frac{|S_{Sd}|}{S_p} < 0.4$

Where

M_{Sd}	is the design moment	Eq. 4.6	DNV OS-F101
S_{Sd}	is the design effective axial force	Eq. 4.8	DNV OS-F101
P_i	is the internal pressure	Table 4-3	DNV OS-F101
P_e	is the external pressure	Sec.4 B200	DNV OS-F101
P_b	is the burst pressure	Eq. 5.8	DNV OS-F101
S_p and M_p	denote the plastic capacities for a pipe	Eq.5.20-5.24	DNV OS-F101
P_{min}	is the minimum internal pressure	Sec.5 D607	DNV OS-F101
P_c	is the characteristic collapse pressure	Eq. 5.10	DNV OS-F101

The other parameters that are included in Equation 3.6 and 3.7 are listed in Table 1 and 2.

3.3 Theory SIMLA

3.3.1 Finite element method

The finite element method is used to create the model in SIMLA. Nodes are defined by attaching them to cartesian-coordinates. When the elements connect to the nodes, the FEM model is created. In the SIMLA script, the NOCOOR command defines the positions of the nodes, and the ELCON command defines how the elements are connected to the nodes. For a more detailed explanation of the FEM formulation see Simla Theory Manual [Sævik, 2017b]

3.3.2 Elements

Pipe 31 is used to build the finite element model of the pipeline. This is a two noded 3D beam element. The element has linear material properties that act elastically. One node is placed on each side of the element. The pipe element is also used to model the vessel.

The orientation of the elements is defined by the position of the vector R shown in Figure 3.3. This vector is defined by specifying the local element system position of the XY-plane relative to the global coordinate system. [Svein Sævik, 2019]. The ELORIENT command controls this orientation. The pipe elements are defined by using coordinates and the seabed elements are defined by using angles instead of coordinates.

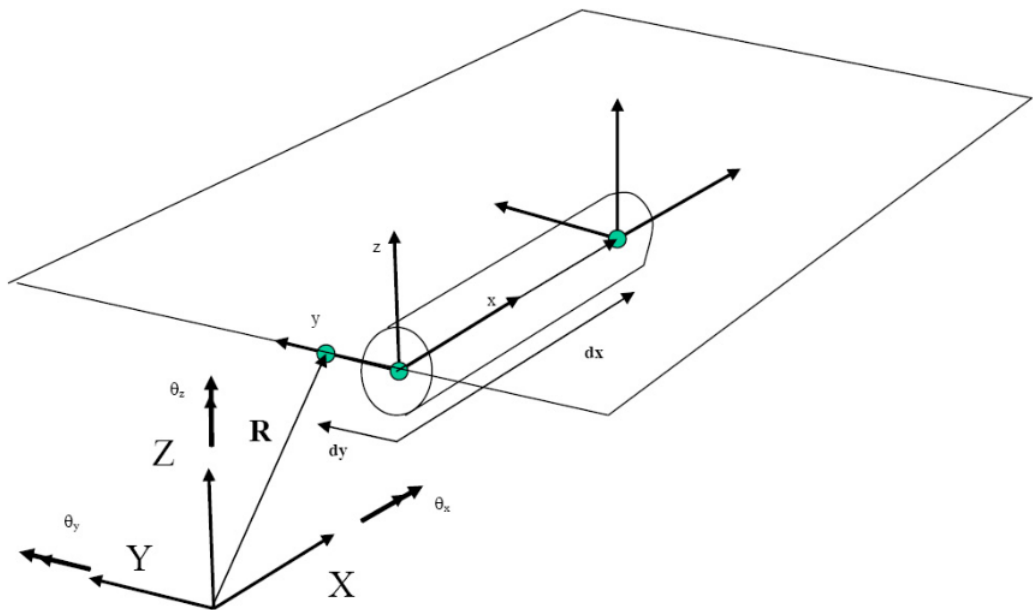


Figure 3.3: Orientation of elements

The seabed element used in the first SIMLA input file for the static equilibrium is CONT125. This is a special element created for simple laying analysis. CONT125 is a one-noded contact element which has no axial spring, only linear springs vertically and transversely to hold the pipe. The seabed contact element is changed to CONT126 when the second SIMLA file for the installation analysis is run. CONT126 includes torsion moment due to axial rotation and transverse displacement. This element can include friction and can use both contact and R contact, which are material cards [Svein Sævik, 2019].

3.3.3 Material soil properties

Two different material soil property cards are used in the analysis. Contact and R contact.

Contact

The contact card allows the pipe to roll on the seabed like a straw rolling on a table. If the friction is too large, the pipe will start to roll along the seabed.

R contact

The R contact card allows the pipe to penetrate and dig itself down in the seabed when it starts to roll or rotate. The rotation of the pipe is handled with a separate spring. The transverse displacement has its own separate spring, in other words, decoupled. The R contact card is closer to describing what happens in real life when the pipe starts to move than the contact card.

3.3.4 Loads

Wave load

The wave load card is used to activate the drag forces, this card assumes a circular cross-section and is governing for pipe 31 element and other pipe and cable element types. When this card is included, the analysis starts to calculate the kinematics because of the velocity of the pipeline. The SIMLA analysis is run with zero wave load, but the card is included to take the drag forces into account.

The parameter study compares the difference if the wave load card is included versus not included. The regular wave in the wave load card is based on the Airy linear wave theory. The wave is set as regular, and the elevation at any point XY along the sea surface is calculated in Equation 3.8, [Svein Sævik, 2019]. Since the wave height is zero, the elevation does not apply. However, it is essential to explain the theory behind the wave load card.

$$\eta(x, y, t) = \frac{H}{2} \sin(\omega t - k)(x - x_0) \cos(\varphi\omega) - k(y - y_0) \sin(\varphi\omega) + \phi \quad (3.8)$$

where:

- H is the wave height
- ω is the wave circle frequency
- t is time
- k is the wave number
- x_0 is the x-coordinate here the wave is generated
- y_0 is the y-coordinate here the wave is generated
- $\varphi\omega$ is wave direction angle
- ϕ is the phase angle

Morison equation for moving body in an oscillatory flow

Equation 3.9 describes the Morison equation for a moving body in an oscillatory flow. The first term is the drag force, the second term is hydrodynamic mass force, and the last term is the Froude- Krylov force. When the hydrodynamic force is zero due to no wave height, the two last terms are zero. The only term that is included in the analysis is the drag force term. This is the reason why the wave load versus no-wave load is interesting to compare, to see how much the drag force contributes to the results in the analysis [Sumer and Fredsøe, 2006]. The load due to current is also zero in the analysis.

$$F = \frac{1}{2} \rho C_D D (U - U_b) |U - U_b| + \rho C_m A (\dot{U} - \dot{U}_b) + \rho A \dot{U} \quad (3.9)$$

where:

- ρ is the density of the water
- \dot{U} is the flow acceleration
- \dot{U}_b is the acceleration of the body
- U is flow velocity
- U_b is the velocity of the moving body
- C_m is the inertia coefficient
- C_D is the drag coefficient
- A is reference area

Laying Scenario

The laying scenario described in this Thesis is defined based on data provided by Equinor. This data is from the Skuld field, which is located in the Norwegian sea. The scenario presented in this chapter is the basic starting scenario. Other scenarios will also be presented in this report to find the optimal laying scenario. One scenario will be referred to as one case in this Thesis. All the basic case data are listed in Table 4.1 and 4.2.

4.1 Pipe

The pipe is divided into different sections through the cross-section. The primary material of the pipe is carbon steel with an ID of 0.3556 m. The carbon steel is metallurgically connected to a cladding section that has a thickness of 0.003m. The outer section of the pipe is covered with an outer coating sheet with a thickness of 0.0748m.

The pipeline in the first case had an imperfection length set to 40m. Pipe data presented in Table 4.1.

Data	Value
ID	0.3556m
t_{steel}	0.022m
$t_{cladding}$	0.003m
t_{coat}	0.0748m
ρ_{steel}	7850kg/m ³
ρ_{coat}	769kg/m ³
OD_{steel}	0.4056m
OD_{total}	0.5552m
Residual curvature	0.01 $\frac{1}{m}$
Imperfection Length	40m

Table 4.1: Pipe data received by Equinor

4.2 Vessel

The vessel that is discussed in this report is chosen to be Deep Blue, see Figure 4.1. This vessel is owned by TechnipFMC and has a high capacity when it comes to subsea installation. The vessel can combine the installation of rigid and flexible risers, flow lines, and umbilicals up to a depth of 3000 m .

The reason this vessel is chosen is because of the large outer diameter of the pipeline. Deep Blue can lay flow lines, using the J-lay method with a max outer diameter of 0.7112 m with a total tension capacity of 770 Te. Another argument for choosing this vessel is the complex design when clad is involved in the pipe data from Equinor.

The J-lay rig provides head clamps that makes it possible to take a pipe with or without collars or friction pads. Rigid pipe straightener is also needed to be able to create imperfections along the pipe. The tower can handle the laying angle of 75° , when the range varies from 58° to 90° . During J-lay, the deck has a storage capacity of 4000 Te. [TechnipFMC, 2012]

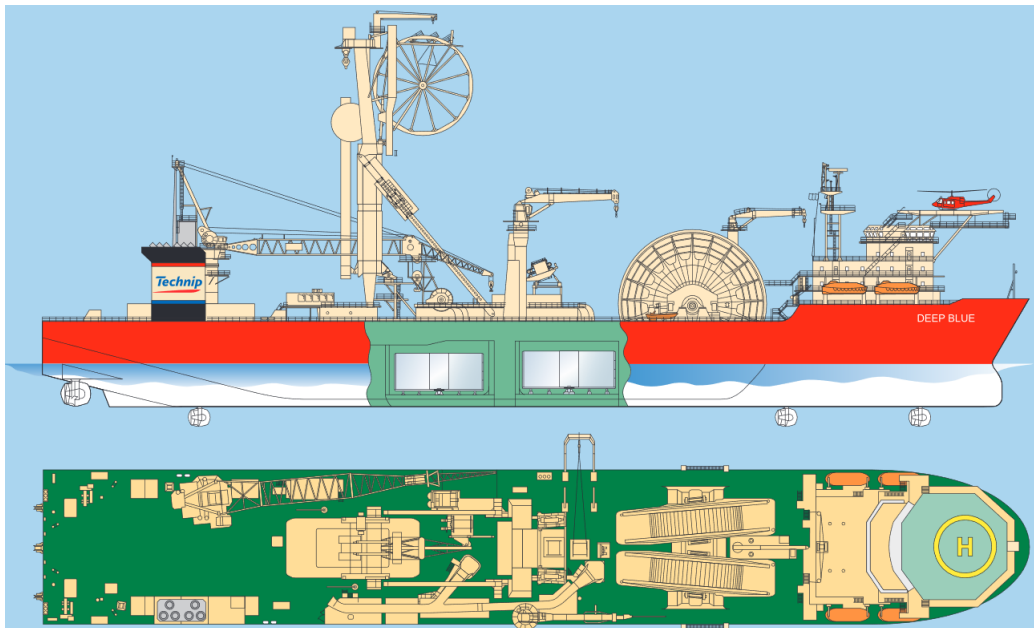


Figure 4.1: Deep Blue

4.3 Environment

The pipeline is installed at the seabed, and the pipeline is submerged in seawater. The depth is set to 380m, and the elevation of the seabed is set as flat. The laying route at the seabed is straight forward. The reason for this is to remove any disturbance if the pipe interact with an un-even seabed or changing the heading of the route. This can result in misleading results due to the additional rotation of the pipe. Laying data provided by Equinor is presented in Table 4.2.

Data	Value
Departure angle	75°
Direction	Straight
Water depth	380m
Seabed type	Flat
Soil Type	Clay
Friction factor Seabed	0.2
Method	J Lay
Density Seawater	1026 $\frac{Kg}{m^3}$

Table 4.2: Laying data received by Equinor

Modeling and analysis

5.1 Analysis

The analysis was built up by using four programs. SIMLA was running the analysis of the laying and operation sequence. SIMPOST is a post-processing tool that took out moments and forces from the results generated by SIMLA. MATLAB was using the axial force and moments and checked if the results were valid. GITBASH, a Linux-based program, was used to run all the programs in a chosen sequence. It was also used to run the parameter study. Every step is illustrated in Figure 5.1

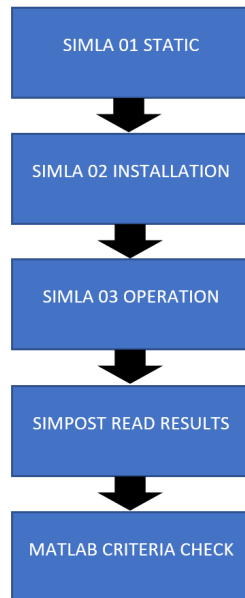


Figure 5.1: Flowchart Analysis

5.2 SIMLA

SIMLA is used to simulate subsea pipelines by using FEM in correlation with dynamics and time. The program was used in this thesis for the analysis of the pipe laying sequence. SIMLA

simulates the laying scenario and analyses the pipe's behavior during the installation and operation of the pipeline. Three input files were used to simulate the whole sequence. These files contain the Finite Element code that sets up the mathematical matrices that need to be solved. The overall SIMLA model is illustrated in Figure 5.2

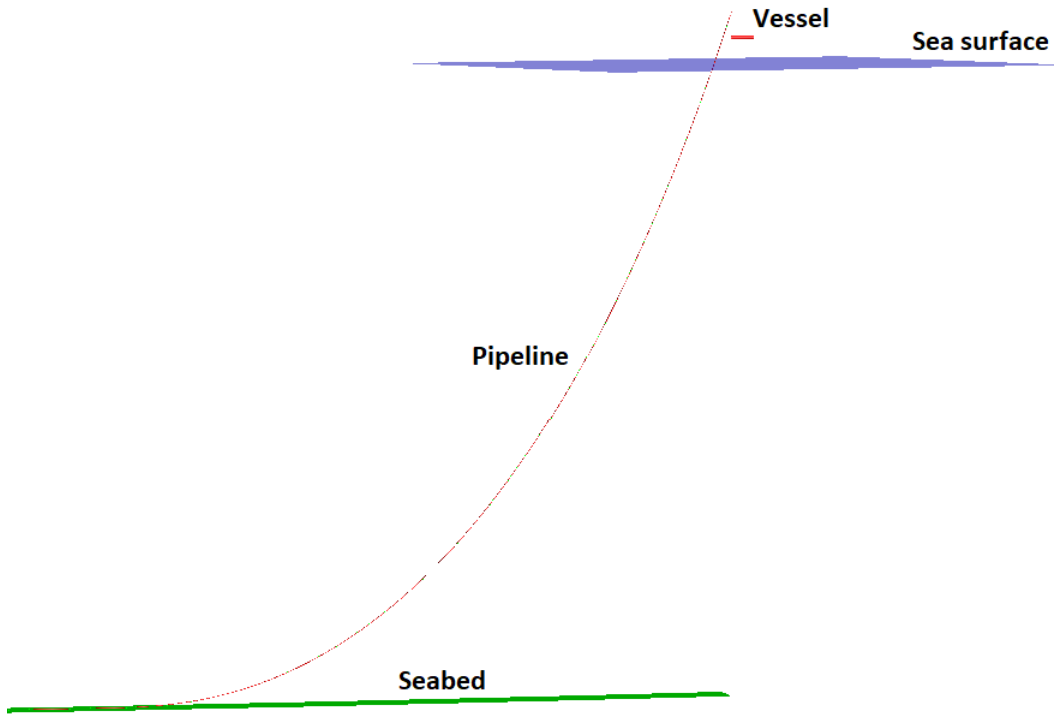


Figure 5.2: SIMLA model

5.2.1 Static Analysis

SIMLA01 was the input file that analyses and sets up the catenary. This file created a static equilibrium between the vessel, pipeline, and seabed. A static equilibrium means that the catenary equations are in equilibrium with each other concerning the laying scenario data described in Chapter 4.

The pipeline was built up by 1000 linear pipe elements (PIPE 31). Each pipe element had two nodes on each side of the pipe that connects the element to the next one; all the elements created the pipeline model.

The seabed was modeled as two squares. The pipe nodes were connected to the seabed nodes in the center of the model. The pipe element touching the seabed was connected to the seabed node. Seabed nodes were defined in a text file.

The contour of the seabed was defined as x-y and z coordinates and the corresponding normal vectors. Since the seabed depth was defined as constant, the z value was set to -380m and did not change during the whole analysis. The normal vectors with direction x and y with respect to the coordinate system, therefore, become zero, and the normal vectors in the z-direction were one due to the constant depth. This means that the vector was pointing straight up towards the vessel. The x coordinate increase with constant increment and y was constant as the route was straight forward. The connection between the pipe and seabed is illustrated in Figure 5.3, where the red circles are the seabed nodes, and the blue lines are the pipe nodes. The vessel was modeled as a single pipe element and the seabed as a 4-noded sea element.

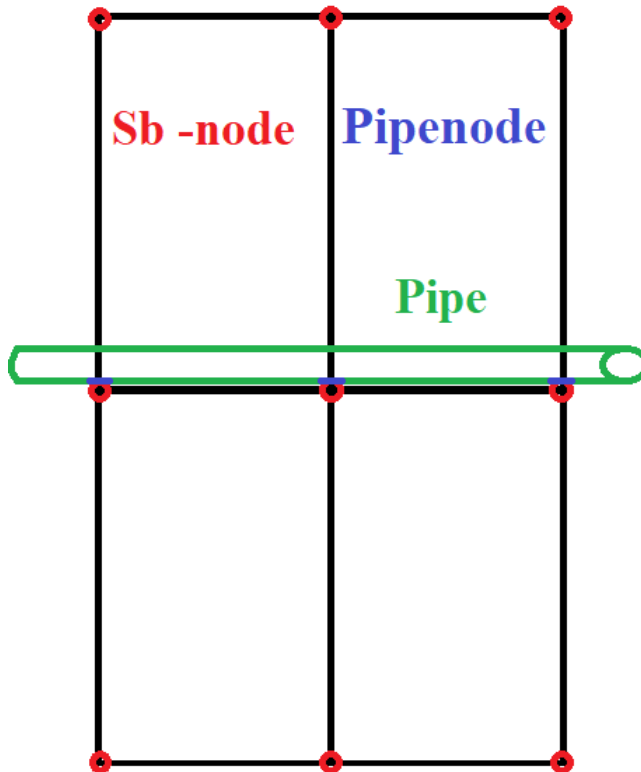


Figure 5.3: Pipe interaction with seabed

After all the elements and nodes were connected, vessel properties, soil properties, seabed properties, the constraints, pipe data, and material were defined. The pipe was constraint at the bottom end where the pipe started at the seabed. The pipe was also constaint at the upper end where the pipe was connected to the vessel. The vessel was fixed in all degrees of freedom (DOF). When the analysis finished, the results were stored in a file called SIMLA01.RAF. For SIMLA01 code see Appendix D.1

5.2.2 Installation Analysis

SIMLA02 was the input file that analyzed the laying sequence. SIMLA02 used the static equilibrium results from SIMLA01 that were stored in the .RAF file as a starting point for the installation analysis. 1500 pipe elements were placed on top of each other at the vessel. This stack of elements was called the FEED group. These elements were fed out and connected to the existing catenary created in SIMLA01. When the vessel started to move, additional seabed elements were added to the model as the vessel moves along the laying route. The route was defined by a text file. Figure 5.4 illustrate how the elements and nodes were connected together in SIMLA02.

The algorithm used to lay the pipe followed the center of the seabed at every step. The pipe node sought the seabed node at the center of the seabed and connected.

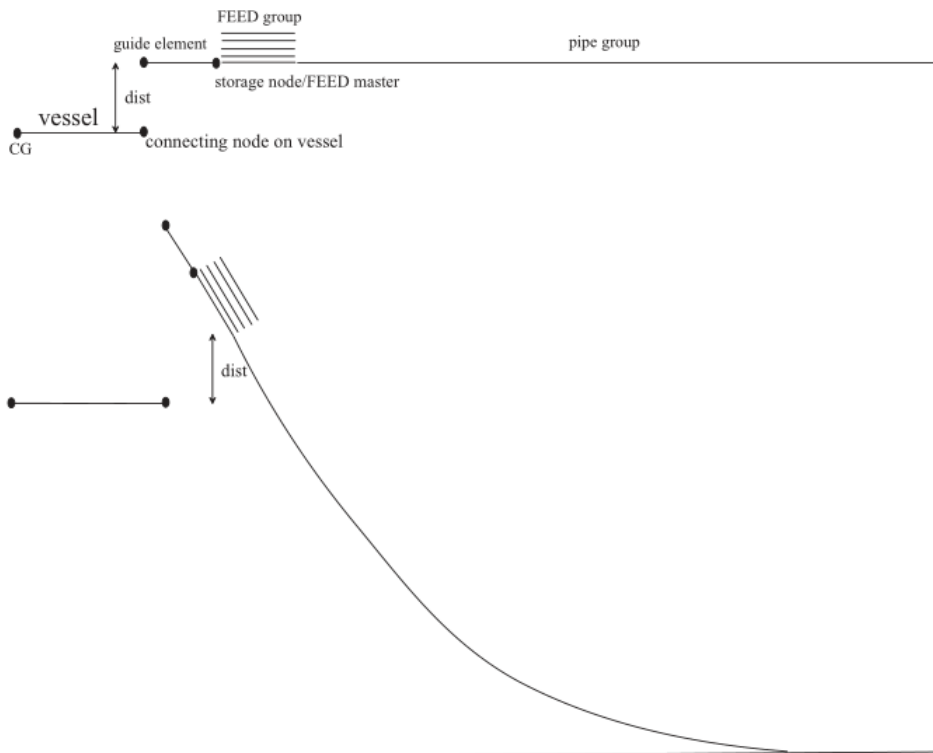


Figure 5.4: Overview setup SIMLA02

The length of the imperfection and the residual curvature was defined in SIMLA02. The imperfection was created by applying curvature about the local y-axis of the element. The curvature was applied at the first element that was fed out until the last chosen element. Each element was 2m, which means that the total length of the imperfection had to be even numbers. The stress free curvature radius is defined as $\frac{1}{\text{Curvature radius}}$. For SIMLA02 code see Appendix D.2

After the installation analysis, the results were post-processed by SIMPOST. This program used the results stored in the .RAF file to create text files.

SIMPOST created six text files:

- Moment Y along the pipeline
- Moment Z along the pipeline
- Axial force along the pipeline
- Axial force at the center of the imperfection related to temperature
- Rotation of the imperfection about X
- Displacement of the vessel

For SIMPOST code see Appendix D.4. The first three files were used to check if the load control condition criteria described in Equation 3.6 were fulfilled. Axial force at the center of the imperfection was used to check how the axial force develops when the temperature and pressure rise. The rotation text file checked if the imperfection rotates, and the Displacement of the vessel text file checked how the vessel moved during the operation. To check if the load control condition criteria were fulfilled, a MATLAB script was created. For MATLAB code, see Appendix D.5.

5.2.3 Operation Analysis

The input file SIMLA03 was analyzing the operation sequence. The input file analyzed the movement of the pipeline when the operating temperature and pressure were applied. This file did almost the same as SIMLA02, but another step that applies pressure and temperature were added. This happened after the pipeline was laid at the seafloor. After the laying sequence was over, the pipeline was fixed on each side of the imperfection. It was essential to have the same length of pipeline that was free to move on each side of the imperfection, as illustrated in Figure 5.5. The constrained pipeline is marked with blue color, the pipeline that is marked as red is free to move.

Five hundred load steps were needed to lay the pipeline in the analysis. After these steps, the pipeline was constrained. The dry mass was added because of the increased weight when the pipeline was filled with oil or gas. The pressure of 20 bar was then applied for the next ten load steps. From 510 to 530 load steps the temperature of 100 degrees C was applied.

SIMPOST was again used to post-process and generate the result files from the analysis. These files were used to check if the imperfection buckles or not. The same as the installation analysis in Subsection 5.2.2. The load control condition criteria were also checked, but since internal pressure was present, Equation 3.7 was used in this case.

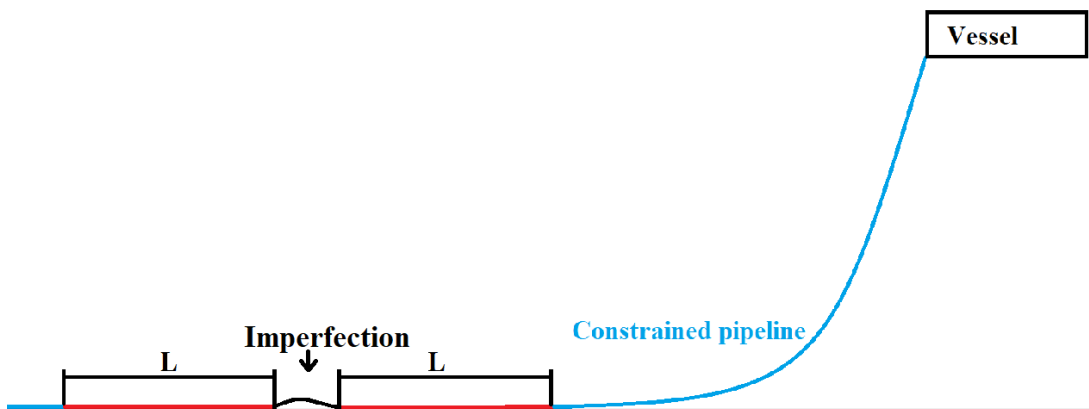


Figure 5.5: Constrained catenary

5.3 MATLAB

MATLAB was used to check the load criteria, and generate all the plots, see Appendix D.5 for the code. MATLAB was also used to read the .MPF files created by SIMPOST, see Appendix D.6 for the MATLAB code. For MATLAB code for combined plots, see Appendix D.7. These scripts were created just for this purpose and to make the check for every analysis easier.

Different analyses were performed in sequence to write out the needed moments and axial forces along the pipeline. This was done to check if the results were valid concerning the load- and displacement controlled condition described in the standard OS-F101.

5.4 Parameter study

GITBASH was used to run the parameter study. The parameter study was set up in a way that moved template files to a directory and modified them. The different templates of the input files that were created at the main directory were called: SIMLA01, SIMLA02, SIMLA03, SIMPOST03, and MATLAB criteria check.

These files defined the parameters that needed to be changed for every iteration. The parameters that were getting changed is listed below:

- Length imperfection
- Departure angle
- Residual curvature
- Torsion moment dependency on the y- displacement
- Torsion moment
- Rotation of pipe
- Torsion spring rotation parameter
- Wave load

To keep track of each analysis, GITBASH created a specific folder for each case. The folder were named in a way which made it easy to see which parameters that were used, like this: (The case number)-(length of the imperfection)-(Departure angle)-(torsion moment dependency on y-direction on/off)-(rotation of pipe on/off)-(torsion moment on/off). An example folder could be:

Case-91-40m-70-R-contact-all-gt1.

Where **R-contact** meant **OFF**, **all** rotation of pipe **OFF**, **gt1** torsion moment **ON**.

Another example could be:

Case-138-10m-70-Contact-4-gt2.

Where **Contact** means **ON**, **-4** rotation of pipe **ON** and **gt2** torsion moment **OFF**.

The reason for R-contact/contact and gt was because of the syntax used in the input files. -4 stood for all DOF constrained except number 4 that controlled the rotation about the global x axis and all stood for all DOF constrained.

Overview of the parameters in Table 5.1

Description	Name	Function
Torsion moment dependency on y-direction	Contact	ON
	R-contact	OFF
Torsion moment	gt1	ON
	gt2	OFF
Rotation of pipe	-4	ON
	all	OFF

Table 5.1: Description parameters

It was essential to set the sequence of the parameter study in the right order. This because the next step was using the results from the previous operation. The sequence of the parameter study is listed below in chronological order.

1. Create folder
2. Copy template files from directory into folder
3. Go into the folder
4. Set parameters
5. Run SIMLA01
6. Run SIMLA02
7. Change name on .RAF file from SIMLA02 to SIMLA03
8. Run SIMLA03
9. Run SIMPOST03
10. Run MATLAB criteria check
11. Go back to main directory

The sequence with different parameters for each case was run after each other. A GITBASH script defined this sequence. For the script, see Appendix D.8. The GITBASH script in the Appendix is an example and only shows a sequence of 2 cases. The original script was way too long and not that interesting when it repeats itself 200 times with different parameters. In this Thesis, six different parts were carried out. This because the results of one sequence raised other interesting questions that needed to be answered to find the optimal laying scenario.

Parameter change

in Table 5.2, 5.3, 5.4, 5.5, 5.6, and 5.7. An overview of each part is presented. Every table shows the different cases and which parameters were being varied.

5.4.1 Part 1

Part 1 of the analysis checked the optimal combination of departure angle, length of imperfection, and residual curvature.

Part1	Cases 1-54					
Parameters						
Angle	70 °	75 °	80 °			
Length imperfection	40m	30m	20m	10m	4m	2m
Residual curvature	0.01	0.015	0.05			
Torsion moment dependency on y-direction	ON					
Torsion moment	ON					
Rotation of pipe	OFF					
Torsion spring rotation parameter	0.1					
Wave load	OFF					

Table 5.2: Part 1 parameter change

5.4.2 Part 2

Part 2 checked the change when the torsion was turned off, the residual curvature set as constant, and the rotation of the pipe varied.

Part2	Cases 55-90					
Parameters						
Angle	70 °	75 °	80 °			
Length imperfection	40m	30m	20m	10m	4m	2m
Residual curvature	0.015					
Torsion moment dependency on y-direction	OFF					
Torsion moment	OFF					
Rotation of pipe	OFF	ON				
Torsion spring rotation parameter	1					
Wave load	OFF					

Table 5.3: Part 2 parameter change

5.4.3 Part 3

Part 3 checked when torsion moment and rotation at the end of the pipe varied, constant residual curvature, and removed imperfection length of 30m.

Part3	Cases 91-150				
Parameters					
Angle	70 °	75 °	80 °		
Length imperfection	40m	20m	10m	4m	2m
Residual curvature	0.015				
Torsion moment dependency on y-direction	OFF				
Torsion moment	ON	OFF			
Rotation of pipe	ON	OFF			
Torsion spring rotation parameter	1				
Wave load	OFF				

Table 5.4: Part 3 parameter change

5.4.4 Part 4

Part 4 was a sensitivity study concerning the stiffness of the torsion spring rotation parameter. This part only varied the TSRP. All the other parameters were constant during the analysis sequence.

Part4	Cases 151-180					
Parameters						
Angle	75 °					
Length imperfection	40m	20m	10m	4m	2m	
Residual curvature	0.015					
Torsion moment dependency on y-direction	OFF					
Torsion moment	ON					
Rotation of pipe	ON					
Torsion spring rotation parameter	0.8	1	1.2	1.4	1.6	1.8
Wave load	OFF					

Table 5.5: Part 4 parameter change

5.4.5 Part 5

Part 5 activated the wave load card to see if it had any effect on the development of the axial force compared to not including the wave load card.

Part5	Cases 181-190				
Parameters					
Angle	75 °				
Length imperfection	40m	20m	10m	4m	2m
Residual curvature	0.015				
Torsion moment dependency on y-direction	OFF				
Torsion moment	ON	OFF			
Rotation of pipe	ON	OFF			
Torsion spring rotation parameter	1				
Wave load	ON				

Table 5.6: Part 5 parameter change

5.4.6 Part 6

Part 6 was a sensitivity study with respect to the stiffness of the torsion spring rotation parameter. This part only varied the TSRP. All the other parameters were constant during the analysis sequence.

Part6	Cases 191-205				
Parameters					
Angle	75 °				
Length imperfection	40m	20m	10m	4m	2m
Residual curvature	0.015				
Torsion moment dependency on y-direction	OFF				
Torsion moment	ON	OFF			
Rotation of pipe	ON	OFF			
Torsion spring rotation parameter	1.2	1.4	1.6		
Wave load	ON				

Table 5.7: Part 6 parameter change

Flowchart of the parameter study is illustrated in Figure 5.6 below. The figure shows when the parameters change during the parameter study and which files that were run after each other.

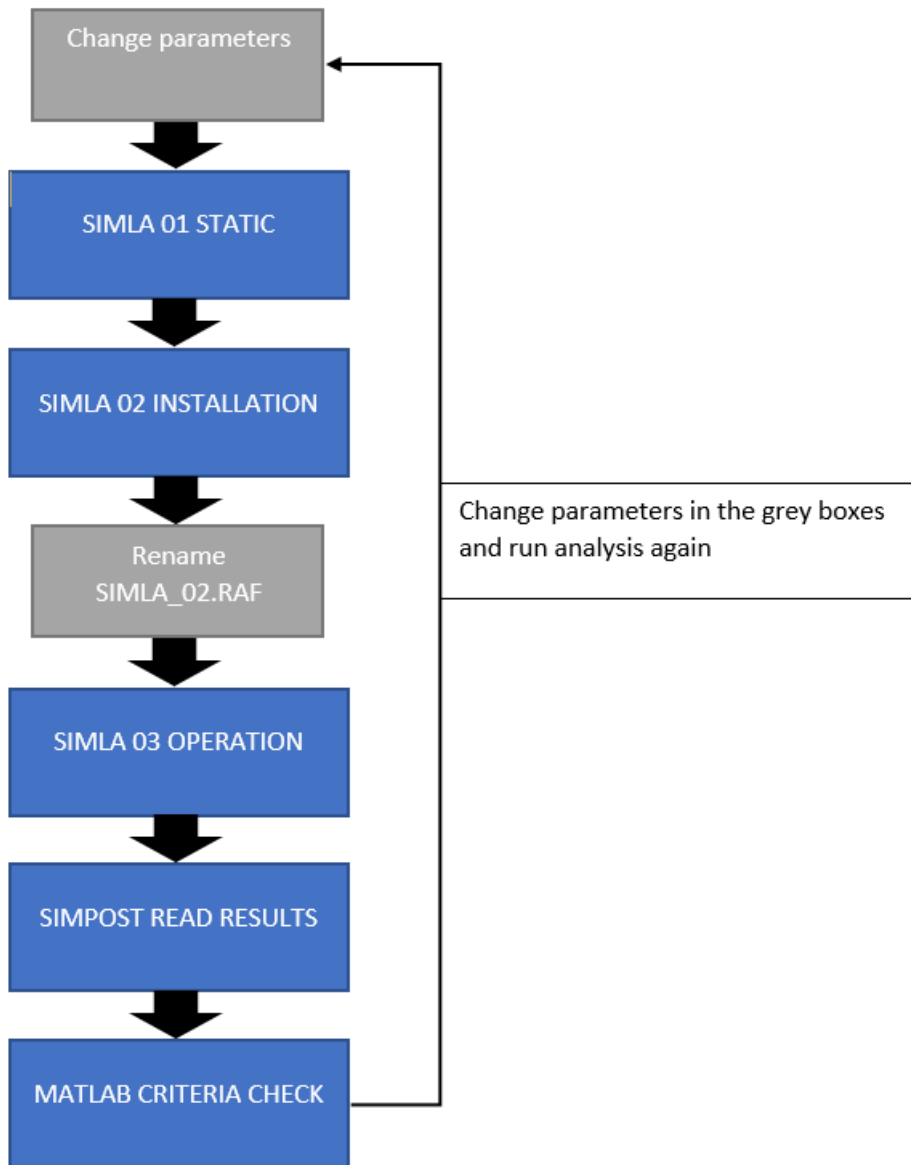


Figure 5.6: Flowchart parameter study

Results and discussion

6.1 Part 1 parameter study

6.1.1 General

Explanation

The results from part 1 of the parameter study are shown in Table 6.1 and 6.2 below. It is important to point out that these analyses were run when the soil material card was described as a contact material type in SIMLA. This means that the torsion moment dependency on y-direction is ON. The column described as "Length" defines the length of the imperfection. "Angle" is the departure angle, and "Res curvature" is the residual curvature. The rotation column defines if the end of the pipe can rotate or not. If the column says ON, the pipe can rotate at the end of the pipe. If it says OFF, the pipe is fixed at the end. The "Torsion" column describes if the torsion moment is on or off. If it says OFF, the torsion moment was set as zero. The columns that are described as crit 1 and crit 2 are respectively installation criteria and operation criteria, for more details for how crit 1 and crit 2 was calculated, see Subsection 3.2. These columns shows the utilization of the load criteria of each laying scenario, where 100% is max. If the installation or operation criteria goes beyond 100%, the case was classified as INVALID. All the invalid and failed cases are marked with red. If the column says, FAIL, the analysis did not converge, and no result is available.

Goal

Part 1 of the parameter study aimed to find a constant residual curvature value that could be used for the next parts of the parameter study. It was essential to pick a robust residual curvature value that utilizes crit 1 and 2. Robust value means that most of the cases for one residual curvature value were valid and close to 100% on both crit 1 and 2. The reason for picking a robust value was that the upcoming parts of the parameter study change other parameters that affect the results. It was vital to pick a robust starting value that can handle these changes.

6.1.2 Results

Table 6.1 and 6.2 list the results form part 1 of the parameter study

Case	Length	Angle	Rotation	Torsion	Res curvature	Crit 1	Crit 2
1	40m	70	ON	OFF	0.01	44%	48%
2	30m	70	ON	OFF	0.01	33%	37%
3	20m	70	ON	OFF	0.01	33%	37%
4	10m	70	ON	OFF	0.01	57%	61%
5	4m	70	ON	OFF	0.01	77%	80%
6	2m	70	ON	OFF	0.01	124%	128%
7	40m	70	ON	OFF	0.015	89%	93%
8	30m	70	ON	OFF	0.015	73%	77%
9	20m	70	ON	OFF	0.015	73%	77%
10	10m	70	ON	OFF	0.015	41%	46%
11	4m	70	ON	OFF	0.015	63%	67%
12	2m	70	ON	OFF	0.015	94%	98%
13	40m	70	ON	OFF	0.05	FAIL	FAIL
14	30m	70	ON	OFF	0.05	714%	718%
15	20m	70	ON	OFF	0.05	714%	718%
16	10m	70	ON	OFF	0.05	150%	154%
17	4m	70	ON	OFF	0.05	36%	40%
18	2m	70	ON	OFF	0.05	59%	63%
19	40m	75	ON	OFF	0.01	43%	47%
20	30m	75	ON	OFF	0.01	37%	41%
21	20m	75	ON	OFF	0.01	32%	36%
22	10m	75	ON	OFF	0.01	57%	61%
23	4m	75	ON	OFF	0.01	78%	82%
24	2m	75	ON	OFF	0.01	116%	120%
25	40m	75	ON	OFF	0.015	91%	95%
26	30m	75	ON	OFF	0.015	70%	74%
27	20m	75	ON	OFF	0.015	70%	74%
28	10m	75	ON	OFF	0.015	42%	46%
29	4m	75	ON	OFF	0.015	65%	69%
30	2m	75	ON	OFF	0.015	94%	98%
31	40m	75	ON	OFF	0.05	FAIL	FAIL
32	30m	75	ON	OFF	0.05	FAIL	FAIL
33	20m	75	ON	OFF	0.05	670%	674%
34	10m	75	ON	OFF	0.05	136%	140%
35	4m	75	ON	OFF	0.05	37%	40%
36	2m	75	ON	OFF	0.05	59%	63%

Table 6.1: Results Part 1

Case	Length	Angle	Rotation	Torsion	Res curvature	Crit 1	Crit 2
37	40m	80	ON	OFF	0.01	50%	54%
38	30m	80	ON	OFF	0.01	45%	49%
39	20m	80	ON	OFF	0.01	36%	40%
40	10m	80	ON	OFF	0.01	57%	61%
41	4m	80	ON	OFF	0.01	79%	83%
42	2m	80	ON	OFF	0.01	110%	114%
43	40m	80	ON	OFF	0.015	95%	99%
44	30m	80	ON	OFF	0.015	67%	71%
45	20m	80	ON	OFF	0.015	67%	71%
46	10m	80	ON	OFF	0.015	43%	47%
47	4m	80	ON	OFF	0.015	66%	70%
48	2m	80	ON	OFF	0.015	93%	97%
49	40m	80	ON	OFF	0.05	FAIL	FAIL
50	30m	80	ON	OFF	0.05	FAIL	FAIL
51	20m	80	ON	OFF	0.05	258%	262%
52	10m	80	ON	OFF	0.05	131%	135%
53	4m	80	ON	OFF	0.05	38%	42%
54	2m	80	ON	OFF	0.05	59%	63%

Table 6.2: Results Part 1

6.1.3 Discussion

Residual curvature

Table 6.1 and 6.2 show that all the cases with residual curvature are within the limit for crit 1 and crit 2. All of the cases with residual curvature of 0.01 is also valid except when the imperfection length is set to 2m. These cases do not utilize the load criteria as much, which means that crit 1 and 2 are far from 100%. By looking at the results, the residual curvature value of 0.015 is the most robust one. Cases with 0.05 either fail or exceed crit 1 and 2 quite often. Residual curvature value is set to 0.015 for the next parts of the parameter study.

Departure Angle

Another thing to point out is that the change in angle does not affect crit 1 and 2 that much. If case 19 is compared to case 1. The change in crit 1 and 2 is only 1%. The only difference between these cases is the change in angle. If looking at cases 19 and 37, the change in crit 1 is 3%, and the change in crit 2 is 7%. These cases all got a residual curvature value of 0.01. If the same comparison is made by cases that have 0.05 as residual curvature value, the change is even smaller when cases 35 and 53 is compared. The change in crit 1 is 1%, and crit 2 is 2% for these cases. It has to be said that the change in departure angle is only 5 degrees. In case 17 and 53, where the change in departure angle is 10 degrees crit 1 and 2 has changed by only 2%.

Length imperfection

It is no clear pattern to point out when the change in imperfection length is discussed. Figure 6.1 illustrates the development in crit 1 and 2 when the imperfection length changes from 40m to 2m. The curve acts exponential, high crit utilization when the length is short.

By looking at the curve for residual curvature of 0.015 in Figure 6.2, the development does not look the same. The crit development when the residual curvature is 0.05 in Figure 6.3 is not close to one of the other graphs. The development of the three graphs got no similarities, and it does not seem like any pattern between them.

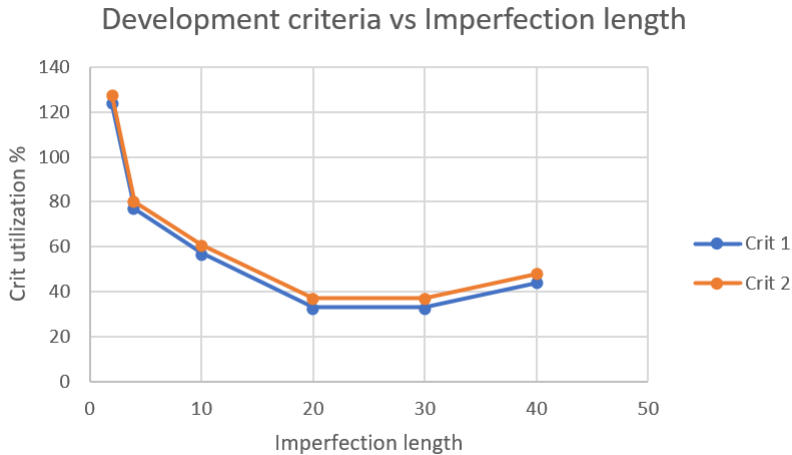


Figure 6.1: Residual curvature 0.01 Case 1-6

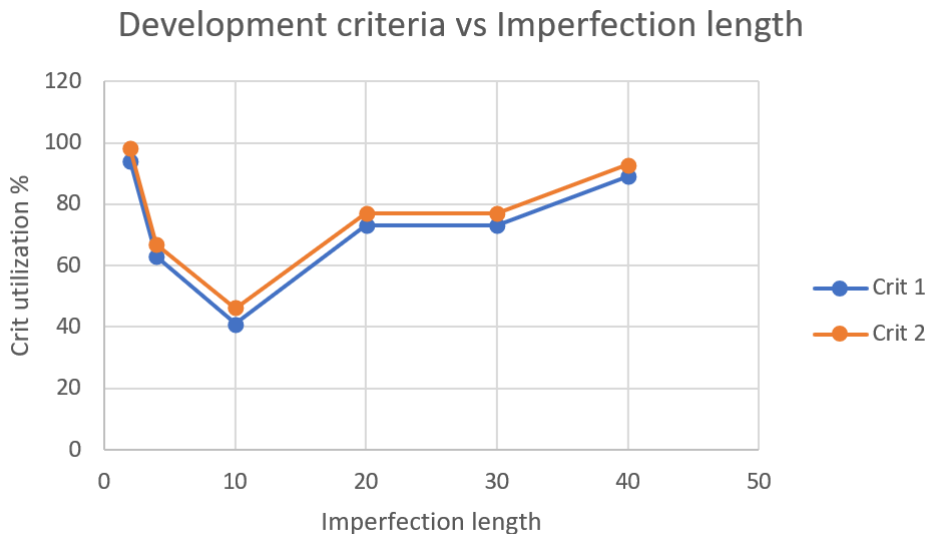


Figure 6.2: Residual curvature 0.015 Case 7-12



Figure 6.3: Residual curvature 0.05 Case 14-18

6.2 Part 2 Parameter study

6.2.1 General

Explanation

Residual curvature value was constant at 0.015 for all the cases as a result of the Part 1 parameter study. It is crucial to point out that the analysis was run when the soil material card is changed to R contact material type. This means that the torsion moment dependency on y-direction was OFF. The R contact card was used for all the parts of the parameter study except part 1. The physical difference is explained in Subsection 3.3.2. The R contact card was closer to describe what happens in real life when the pipe starts to move than the contact card. For the analysis to converge, the Torsion spring rotation parameter was changed to 1 in the R contact card.

Goal

The first goal of part 2 of the parameter study was to compare the results when the R contact card was used instead of the contact card. The second goal was to compare if the pipe can rotate at the end or not.

6.2.2 Results

Table 6.3 and 6.4 list the results form part 2 of the parameter study.

Case	Length	Angle	Rotation	Torsion	Crit 1	Crit 2
55	40m	70	ON	OFF	89%	93%
56	30m	70	ON	OFF	73%	77%
57	20m	70	ON	OFF	73%	77%
58	10m	70	ON	OFF	42%	46%
59	4m	70	ON	OFF	63%	67%
60	2m	70	ON	OFF	94%	98%
61	40m	75	ON	OFF	91%	95%
62	30m	75	ON	OFF	73%	77%
63	20m	75	ON	OFF	73%	77%
64	10m	75	ON	OFF	42%	46%
65	4m	75	ON	OFF	65%	69%
66	2m	75	ON	OFF	94%	98%
67	40m	80	ON	OFF	95%	99%
68	30m	80	ON	OFF	67%	71%
69	20m	80	ON	OFF	67%	71%
70	10m	80	ON	OFF	43%	47%
71	4m	80	ON	OFF	66%	70%
72	2m	80	ON	OFF	93%	97%

Table 6.3: Results Part 2

Case	Length	Angle	Rotation	Torsion	Crit 1	Crit 2
73	40m	70	OFF	OFF	89%	93%
74	30m	70	OFF	OFF	73%	77%
75	20m	70	OFF	OFF	73%	77%
76	10m	70	OFF	OFF	33%	37%
77	4m	70	OFF	OFF	63%	67%
78	2m	70	OFF	OFF	94%	98%
79	40m	75	OFF	OFF	FAIL	FAIL
80	30m	75	OFF	OFF	70%	74%
81	20m	75	OFF	OFF	70%	74%
82	10m	75	OFF	OFF	42%	46%
83	4m	75	OFF	OFF	65%	69%
84	2m	75	OFF	OFF	94%	98%
85	40m	80	OFF	OFF	95%	99%
86	30m	80	OFF	OFF	67%	71%
87	20m	80	OFF	OFF	67%	71%
88	10m	80	OFF	OFF	43%	47%
89	4m	80	OFF	OFF	66%	70%
90	2m	80	OFF	OFF	93%	97%

Table 6.4: Results Part 2

6.2.3 Discussion

Departure angle

All cases are valid except case 79. Case 79 did not converge when SIMLA tried to lay the pipe at the seabed. It seems strange that when the departure angle is either 70 or 80 degrees, the analysis converges but does not converge when the departure angle is in between at 75 degrees.

Length imperfection

The development in crit 1 and 2, when the imperfection length changes from 40m to 2m, is illustrated in Figure 6.4 for case 55-60. If cases 73-78 are compared when the rotation is OFF, the only change in development is at an imperfection length of 10 m.

Crit 1 and crit 2 from case 7-12 in Table 6.1 is the same as case 55-60 in Table 6.3. That means that the R contact versus contact got no impact when "Rotation" is ON, and "Torsion" is OFF, this is not so strange when "Torsion" is OFF in both cases, the difference will show when "Torsion" is ON.

Uncertainties

The torsion spring rotation parameter was set to 1, which is high. This was done because the analysis did not converge at a lower value. This might lead to the pipe not behaving as it would do in real life. The reason is that the higher the value of the TSRP, the more slack the torsion spring stiffness has.



Figure 6.4: Residual curvature 0.015 Case 55-60



Figure 6.5: Residual curvature 0.015 Case 7-12

6.3 Part 3 Parameter study

6.3.1 General

Explanation

Table 6.5 and 6.6 show the results from part 3 of the parameter study. Two additional columns are added to the table. "Buckle" confirms if the case buckles in a controlled manner. PEAK means that the axial force is high and must be taken into account. "Rotation imp" describes if the pipe rotates in a way that the imperfection is on the side and in contact with the seabed after the installation analysis is finished. Imperfection length of 30m was removed due to identical results for imperfection length of 20m. Every possible combination of torsion moment ON/OFF and rotation ON/OFF were analyzed in part 3.

Goal

The first goal of part 3 was to check crit 1 and 2 for every possible combination with rotation ON/OFF and torsion ON/OFF, and compare the differences. The second goal was to check if the imperfection rotates and buckles as wanted.

6.3.2 Results

Table 6.5 and 6.6 list the results form part 3 of the parameter study.

Case	Length	Angle	Rotation	Torsion	Crit 1	Crit 2	Buckle	Rotation imp
91	40m	70	OFF	ON	89%	93%	VALID	YES
92	20m	70	OFF	ON	73%	77%	VALID	NO
93	10m	70	OFF	ON	42%	46%	VALID	NO
94	4m	70	OFF	ON	63%	67%	PEAK	NO
95	2m	70	OFF	ON	94%	98%	PEAK	NO
96	40m	75	OFF	ON	FAIL	FAIL	FAIL	FAIL
97	20m	75	OFF	ON	70%	74%	VALID	NO
98	10m	75	OFF	ON	42%	46%	VALID	NO
99	4m	75	OFF	ON	65%	69%	PEAK	NO
100	2m	75	OFF	ON	94%	98%	PEAK	NO
101	40m	80	OFF	ON	91%	95%	VALID	YES
102	20m	80	OFF	ON	70%	74%	VALID	NO
103	10m	80	OFF	ON	42%	46%	VALID	NO
104	4m	80	OFF	ON	65%	69%	PEAK	NO
105	2m	80	OFF	ON	94%	98%	PEAK	NO
106	40m	70	OFF	OFF	89%	93%	VALID	YES
107	20m	70	OFF	OFF	73%	77%	VALID	NO
108	10m	70	OFF	OFF	42%	46%	VALID	NO
109	4m	70	OFF	OFF	63%	67%	PEAK	NO
110	2m	70	OFF	OFF	94%	98%	PEAK	NO

Table 6.5: Results Part 3

Case	Length	Angle	Rotation	Torsion	Crit 1	Crit 1	Buckle	Rotation imp
111	40m	75	OFF	OFF	FAIL	FAIL	FAIL	FAIL
112	20m	75	OFF	OFF	70%	74%	VALID	YES
113	10m	75	OFF	OFF	42%	46%	VALID	NO
114	4m	75	OFF	OFF	65%	69%	PEAK	NO
115	2m	75	OFF	OFF	94%	98%	PEAK	NO
116	40m	80	OFF	OFF	91%	95%	VALID	YES
117	20m	80	OFF	OFF	70%	74%	VALID	YES
118	10m	80	OFF	OFF	42%	46%	VALID	NO
119	4m	80	OFF	OFF	65%	69%	PEAK	NO
120	2m	80	OFF	OFF	94%	98%	PEAK	NO
121	40m	70	ON	ON	FAIL	FAIL	FAIL	FAIL
122	20m	70	ON	ON	FAIL	FAIL	FAIL	FAIL
123	10m	70	ON	ON	FAIL	FAIL	FAIL	FAIL
124	4m	70	ON	ON	FAIL	FAIL	FAIL	FAIL
125	2m	70	ON	ON	FAIL	FAIL	FAIL	FAIL
126	40m	75	ON	ON	FAIL	FAIL	FAIL	FAIL
127	20m	75	ON	ON	FAIL	FAIL	FAIL	FAIL
128	10m	75	ON	ON	FAIL	FAIL	FAIL	FAIL
129	4m	75	ON	ON	FAIL	FAIL	FAIL	FAIL
130	2m	75	ON	ON	FAIL	FAIL	FAIL	FAIL
131	40m	80	ON	ON	FAIL	FAIL	FAIL	FAIL
132	20m	80	ON	ON	FAIL	FAIL	FAIL	FAIL
133	10m	80	ON	ON	FAIL	FAIL	FAIL	FAIL
134	4m	80	ON	ON	FAIL	FAIL	FAIL	FAIL
135	2m	80	ON	ON	FAIL	FAIL	FAIL	FAIL
136	40m	70	ON	OFF	89%	93%	VALID	YES
137	20m	70	ON	OFF	73%	77%	VALID	YES
138	10m	70	ON	OFF	42%	46%	VALID	NO
139	4m	70	ON	OFF	63%	67%	PEAK	NO
140	2m	70	ON	OFF	94%	98%	PEAK	NO
141	40m	75	ON	OFF	91%	95%	VALID	YES
142	20m	75	ON	OFF	70%	74%	VALID	YES
143	10m	75	ON	OFF	42%	46%	VALID	NO
144	4m	75	ON	OFF	65%	69%	PEAK	NO
145	2m	75	ON	OFF	94%	98%	PEAK	NO
146	40m	80	ON	OFF	91%	95%	VALID	YES
147	20m	80	ON	OFF	70%	74%	VALID	YES
148	10m	80	ON	OFF	42%	46%	VALID	NO
149	4m	80	ON	OFF	65%	69%	PEAK	NO
150	2m	80	ON	OFF	94%	98%	PEAK	NO

Table 6.6: Results Part 3

6.3.3 Discussion

Departure angle

None of the cases with departure angle 75 imperfection length 40m and "Rotation" OFF converge. Failure when both "Rotation" OFF and "Torsion" OFF was expected when case 79 in part 2 failed with the same parameters, but not when "Torsion" is ON.

Length imperfection

Figure 6.6 and Figure 6.7 illustrate the development in axial force with respect to "Rotation" ON/OFF at imperfection length 40m. The development in axial force does not vary that much and is pretty much the same. The same goes for imperfection length 10m (Figure 6.10 and 6.11), 4 m (Figure 6.12 and 6.13), imperfection length 2m (Figure 6.14 and 6.15). Imperfection length of 20m, on the other hand, is not that similar.

The development of the axial force for Case 112 and 117 differs from the other cases in Figure 6.8. The reason for this is that the imperfection in Case 112 and 117 rotates. When the imperfection rotates, the max axial force is lower, and the utilization of crit 1 and 2 are higher than when the imperfection does not rotate. For plot of the rotation of the imperfection about the X-axis see Figure 6.16 and Figure 6.17. The plots show that the two cases rotate in the same way. The imperfection only ends up rotating 70 degrees, which means that the pipe does not lay flat on the seabed. At the end of the operational sequence, at load step 1500, the pipe starts to rotate back and forth; this is because the temperature is rising; it does not seem like the rotation pulse stops before the temperature stop increasing when analysis has ended. For the plot of the development of the axial force for each case, see Appendix C.1, for rotation of the imperfection, see Appendix C.2.

The column that says "PEAK" means that the axial force is high and has a higher amplitude that varies. In Figure 6.18, case 141-145 are plotted in the same graph. When looking at the graph, it is clear that cases 144 and 145 are classified as "PEAK" compared to the other cases. All cases that are classified as "PEAK" has an imperfection length of either 2m or 4m. This because the axial force needs to be higher for the imperfection to buckle when the imperfection is small.

Torsion

When "Torsion" is ON, and "Rotation" is ON, all the cases fail. Torsion is the twisting of an object to an applied torque. When the pipe has "Rotation" ON, this twisting is harder to do, making the analysis harder to converge. Therefore the case fails.

Rotation

All the cases with 40m imperfection length rotate if they converge. Some of the cases with 20m imperfection length also rotates, but not all of them. When "Torsion" is turned ON, none of the cases rotate. When "Torsion" is turned OFF, all cases rotate except case 107 when the departure angle is 70 degrees.

Figure 6.19 shows how case 91 rotates. The imperfection starts to rotate when the imperfection reaches the seabed at load step 170. It rotates 95 degrees before it starts to rotate the other way at load step 200. The imperfection rotates the opposite way to 0 degrees and keeps on going until it reaches 50 degrees, from there it slowly rotates to about 75 degrees when the analysis has finished.

Conservative assumption

The most conservative configuration is when "Rotation" is OFF, and "Torsion" is ON. The least conservative case is the opposite when the "Rotation" is ON and "Torsion" is OFF. Somewhere in between these two configurations is where the realistic case lies. From an engineering perspective, the most conservative case will be the preferred one to draw any conclusion from. Therefore, an imperfection length of 40m will be the most optimal one.

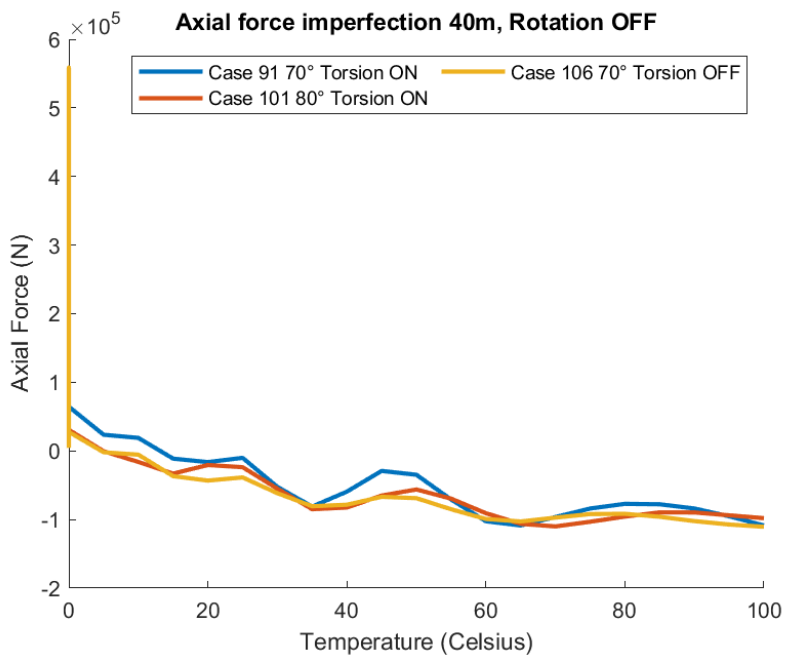


Figure 6.6: Axial force imperfection 40m, Rotation off

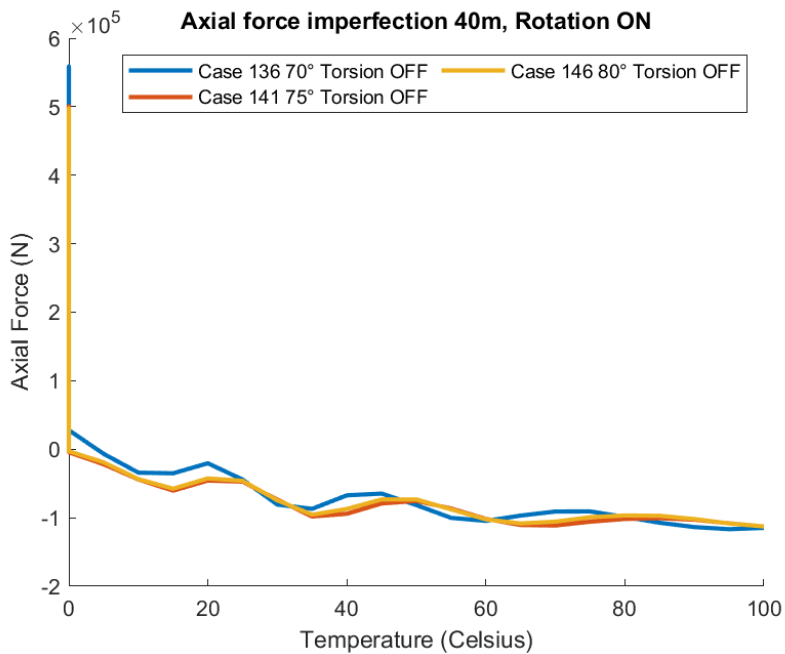


Figure 6.7: Axial force imperfection 40m, Rotation on

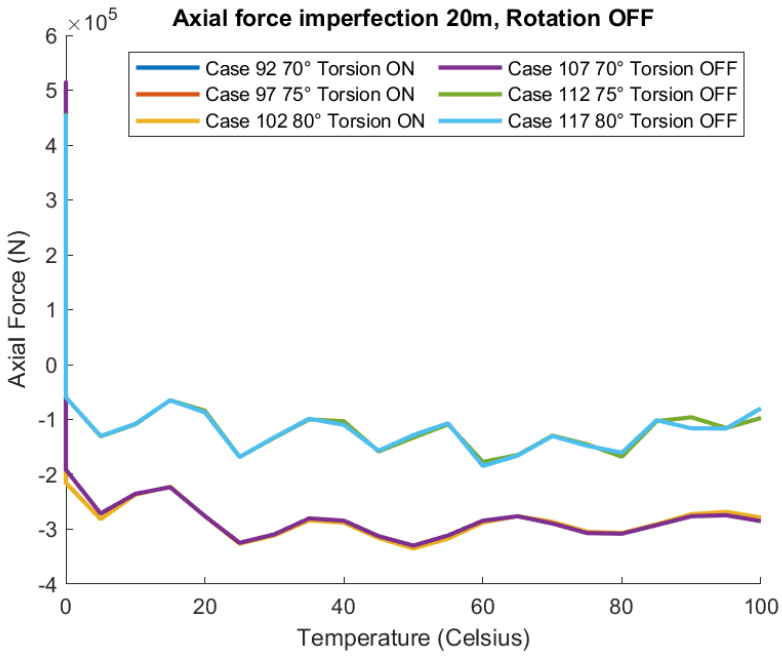


Figure 6.8: Axial force imperfection 20m, Rotation off

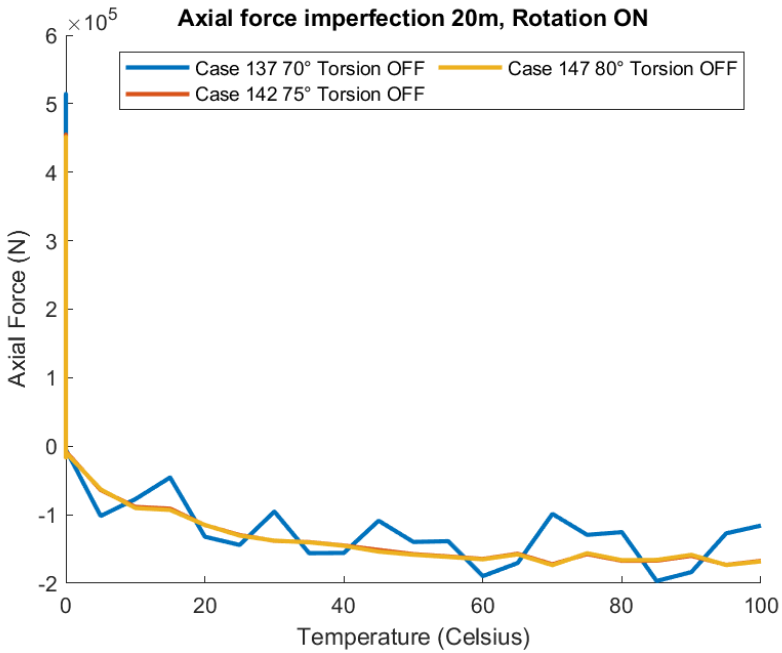


Figure 6.9: Axial force imperfection 20m, Rotation on

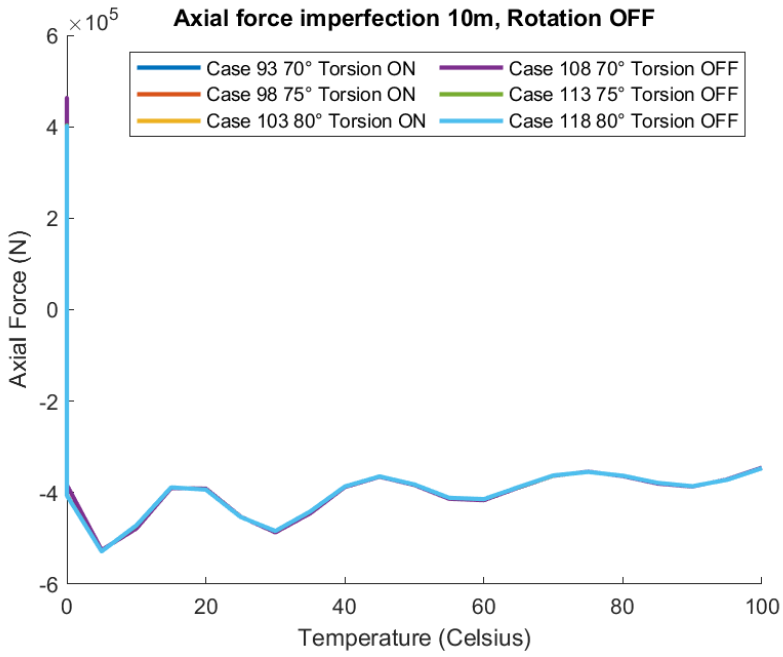


Figure 6.10: Axial force imperfection 10m, Rotation off

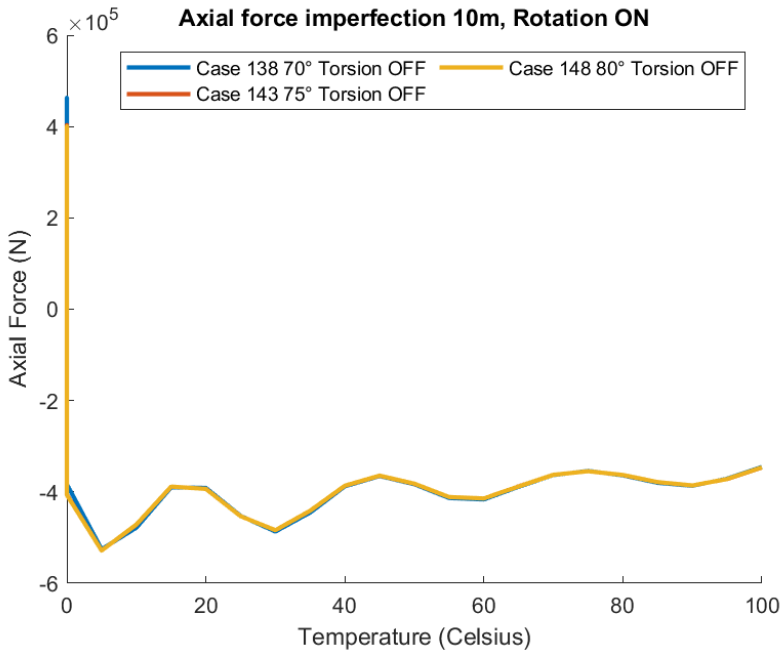


Figure 6.11: Axial force imperfection 10m, Rotation on

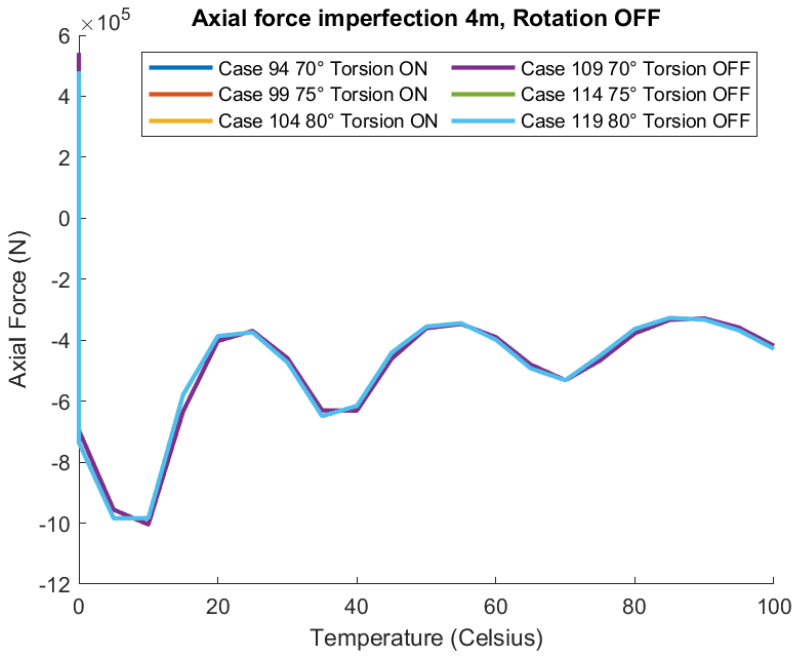


Figure 6.12: Axial force imperfection 4m, Rotation off

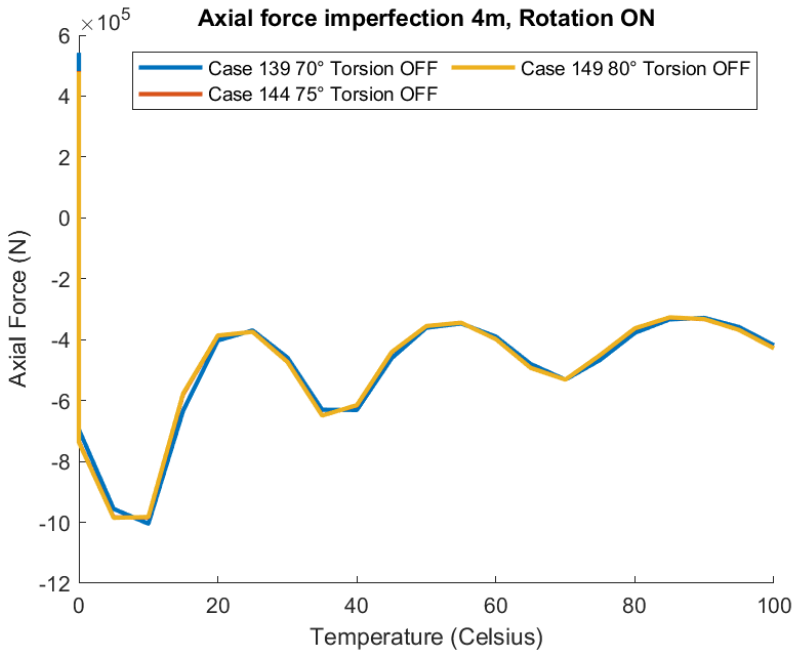


Figure 6.13: Axial force imperfection 4m, Rotation on

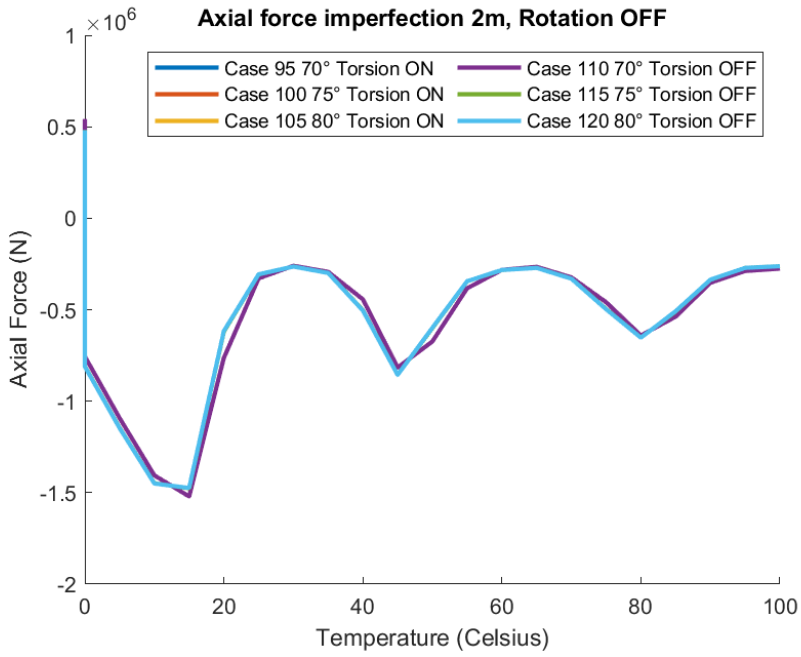


Figure 6.14: Axial force imperfection 2m, Rotation off

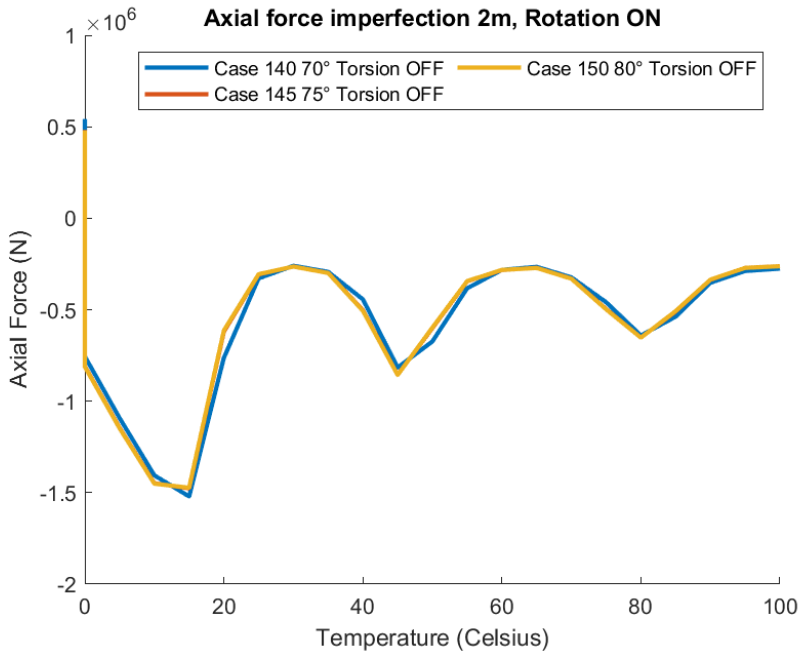


Figure 6.15: Axial force imperfection 2m, Rotation on

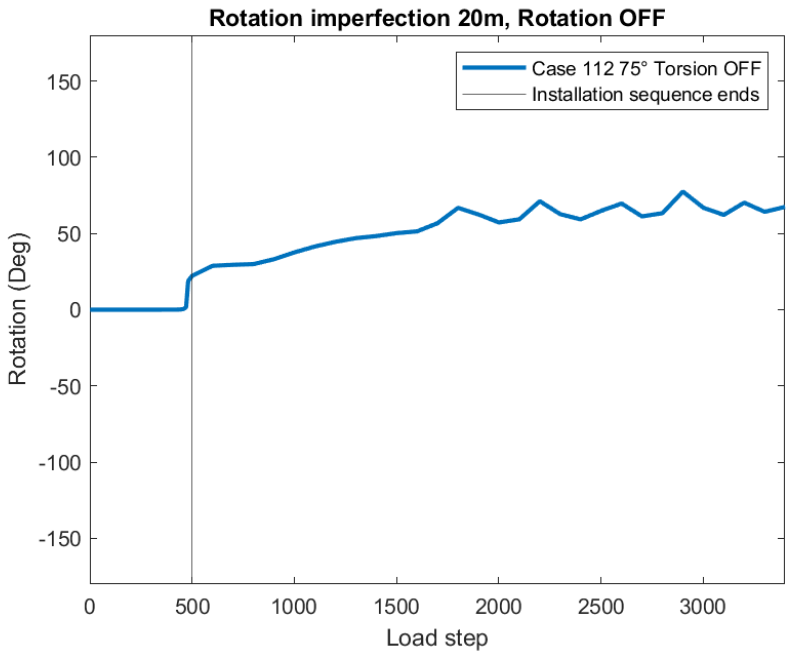


Figure 6.16: Rotation case 112

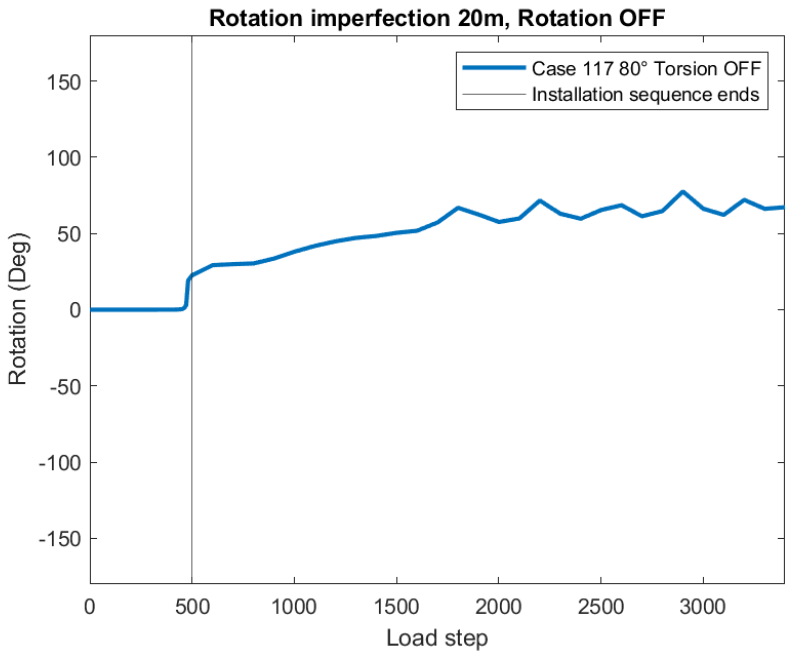


Figure 6.17: Rotation case 117

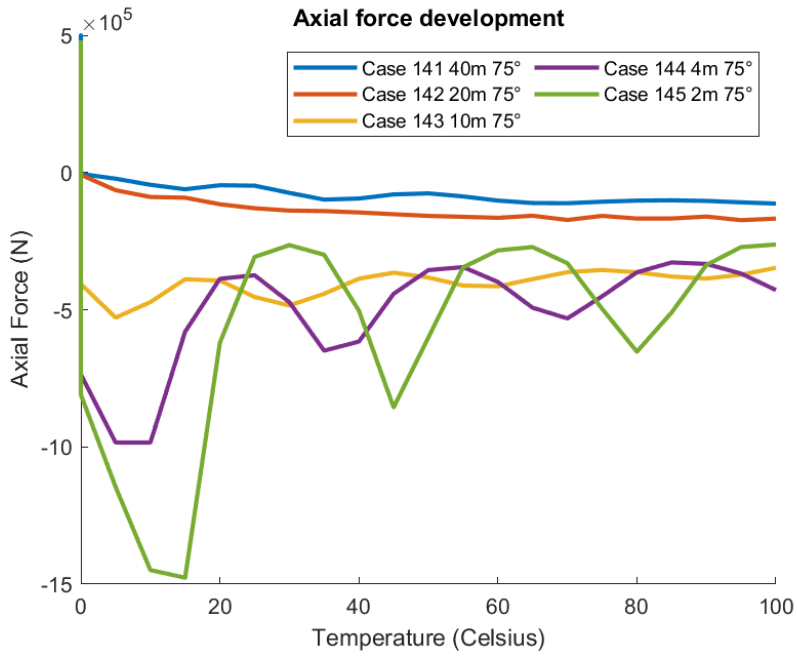


Figure 6.18: Axial force development case 141-145

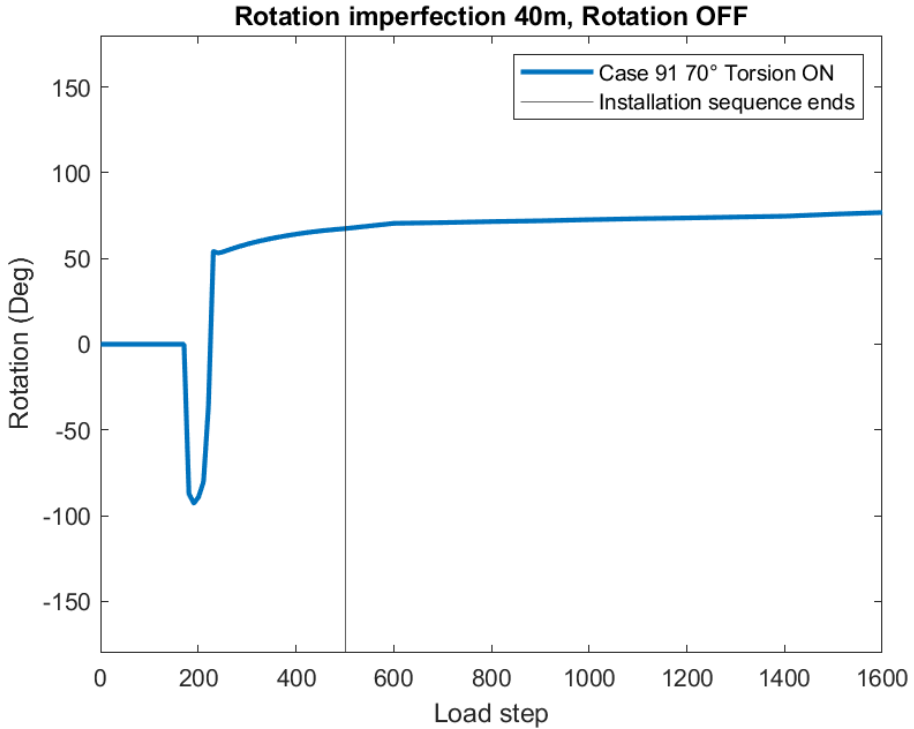


Figure 6.19: Rotation case 91

6.4 Part 4 Parameter study

6.4.1 General

Explanation

In part 4 , cases 121-135 all failed. These cases have; "Rotation" ON and "Torsion" ON. The torsion spring rotation parameter has been an essential factor for cases to converge. This value controls how slack the torsion spring is. It was, therefore, interesting to see at what value these cases converge. A sensitivity study concerning the TSRP was the main focus in this part. With a higher value of the TSRP, the twist of the pipe due to an applied torque is easier to achieve, which makes the analysis easier to converge.

Goal

The goal was to make case 126-130 converge and check the sensitivity of the TSRP.

6.4.2 Results

Table 6.7 list the results form part 4 of the parameter study. The range for the TSRP was set from 0.8 to 1.8 with a step increment of 0.2.

Case	Length	Torsion spring rotation parameter	Crit 1	Crit 2	Buckle	Rotation imp
151	40m	0.8	FAIL	FAIL	FAIL	FAIL
152	20m	0.8	FAIL	FAIL	FAIL	FAIL
153	10m	0.8	FAIL	FAIL	FAIL	FAIL
154	4m	0.8	FAIL	FAIL	FAIL	FAIL
155	2m	0.8	FAIL	FAIL	FAIL	FAIL
156	40m	1	FAIL	FAIL	FAIL	FAIL
157	20m	1	FAIL	FAIL	FAIL	FAIL
158	10m	1	FAIL	FAIL	FAIL	FAIL
159	4m	1	FAIL	FAIL	FAIL	FAIL
160	2m	1	FAIL	FAIL	FAIL	FAIL
161	40m	1.2	91%	95%	VALID	YES
162	20m	1.2	FAIL	FAIL	FAIL	FAIL
163	10m	1.2	FAIL	FAIL	FAIL	FAIL
164	4m	1.2	FAIL	FAIL	FAIL	FAIL
165	2m	1.2	FAIL	FAIL	FAIL	FAIL
166	40m	1.4	FAIL	FAIL	FAIL	FAIL
167	20m	1.4	FAIL	FAIL	FAIL	FAIL
168	10m	1.4	42%	46%	VALID	NO
169	4m	1.4	65%	69%	PEAK	NO
170	2m	1.4	94%	98%	PEAK	NO

Table 6.7: Results Part 4

Case	Length	Torsion spring rotation parameter	Crit 1	Crit 2	Buckle	Rotation imp
171	40m	1.6	91%	95%	VALID	YES
172	20m	1.6	70%	74%	VALID	NO
173	10m	1.6	42%	46%	VALID	NO
174	4m	1.6	65%	69%	PEAK	NO
175	2m	1.6	94%	98%	PEAK	NO
176	40m	1.8	91%	95%	VALID	YES
177	20m	1.8	70%	74%	VALID	NO
178	10m	1.8	42%	46%	VALID	NO
179	4m	1.8	65%	69%	PEAK	NO
180	2m	1.8	94%	98%	PEAK	NO

Table 6.8: Results Part 4

6.4.3 Discussion

Torsion spring rotation parameter

All cases converge with a TSRP of 1.6, which is quite high. Strangely, case 161 converge, but case 166 does not. Case 161 got 0.2 lower TSRP than 166. These two cases have identical parameters except the TSRP and should converge. It might be that the TSRP is not the only parameter that makes these cases converge. This has to be a numerical issue.

The value of 1.6 is high but is needed to make all the imperfection lengths in the analysis converge. This high value must be kept in mind when discussing which case to recommend for further studies.

6.5 Part 5 Parameter study

6.5.1 General

Explanation

The results in Table 6.9 included the wave load card in the analysis. Table 6.10 is included to see the difference in criteria and if the pipe rotates and buckles as intended. Results from part 2 with cases 96-100 and 141-145, when the wave load card is not included, are listed in Table 6.10 .

The wave load is set as 0 in cases 181-190 to see if including this card will have an effect on the axial force. Figure 6.20, 6.21, 6.22, 6.23 and 6.24 illustrate the difference in axial force at the imperfection when the wave load card is included versus not include. Figure 6.25 and 6.26 illustrate how the imperfection rotates. Figure 6.27 and 6.28 describes how the vessel moves during the installation sequence.

Goal

The first goal for this part was to compare when including the wave load card versus not include it. The second goal was to check how the vessel moves during the laying sequence.

6.5.2 Results

Table 6.9 list the results form part 5 of the parameter study. Table 6.10 lists the results from part 3 and is shown below for easier comparison.

Case	Length	Angle	Rotation	Torsion	Crit 1	Crit 1	Buckle	Rotation imp
181	40m	75	ON	OFF	91%	95%	VALID	YES
182	20m	75	ON	OFF	70%	74%	VALID	YES
183	10m	75	ON	OFF	42%	46%	VALID	NO
184	4m	75	ON	OFF	65%	69%	PEAK	NO
185	2m	75	ON	OFF	94%	98%	PEAK	NO
186	40m	75	OFF	ON	FAIL	FAIL	FAIL	FAIL
187	20m	75	OFF	ON	70%	74%	VALID	NO
188	10m	75	OFF	ON	FAIL	FAIL	FAIL	FAIL
189	4m	75	OFF	ON	FAIL	FAIL	FAIL	FAIL
190	2m	75	OFF	ON	56%	60%	PEAK	NO

Table 6.9: Results Part 5

Case	Length	Angle	Rotation	Torsion	Crit 1	Crit 1	Buckle	Rotation imp
141	40m	75	ON	OFF	91%	95%	VALID	YES
142	20m	75	ON	OFF	70%	74%	VALID	YES
143	10m	75	ON	OFF	42%	46%	VALID	NO
144	4m	75	ON	OFF	57%	60%	PEAK	NO
145	2m	75	ON	OFF	56%	60%	PEAK	NO
96	40m	75	OFF	ON	FAIL	FAIL	FAIL	FAIL
97	20m	75	OFF	ON	70%	74%	VALID	NO
98	10m	75	OFF	ON	42%	46%	VALID	NO
99	4m	75	OFF	ON	65%	69%	PEAK	NO
100	2m	75	OFF	ON	94%	98%	PEAK	NO

Table 6.10: Results Part 5

6.5.3 Discussion

Imperfection length

When the length of the imperfection is 40m or 20m, the difference in the development of the axial force is nearly nothing. See Figure 6.20 . When the imperfection length shortens, the difference is clearer. See Figure 6.24

At case 185, when the imperfection length is 2m, the damping effect is much more apparent. This is because the velocity of the pipe when the temperature rises is larger when it comes to shorter imperfection length. When the velocity is larger, the drag forces make a bigger contribution. The velocity of the pipe is smaller when the imperfection length is larger.

Wave load card

The difference when the wave load card was included is that the max axial force is higher when it comes to imperfection length of 4m and 2m. The graph varies less and develops smoother when the temperature rises. The wave load card acts like a damping force. Including this card gives a more realistic result due to the Morison equation attribution to drag.

It is a difference when the wave load card is included when "Rotation" is OFF and "Torsion" ON. Both 10m and 4m fails compared to when the wave load card is OFF. This configuration is the most conservative assumption concerning what will be realistic.

Load criteria

When considering the load criteria, the utilization is much higher for 4m and 2m, the reason for the change is that the maximum axial force is higher. It is also important to point out that the development in the axial force is nearly identical when the pipeline rotates at 40m and 20m, see Figure 6.20 and 6.21.

Rotation

Case 181 and 182 rotate differently. Case 181 at 40m imperfection length stabilises at -55 degrees, see Figure 6.25.

Case 182 starts to rotate in the same way but rotates back and stabilizes at 75 degrees. See Figure 6.26. By these results, it is clear that the imperfection's length has a significant impact on how the imperfection rotates.

Setting "Rotation" ON is the most common thing to do because the end of the pipe is usually laid loose at the seabed when the laying sequence starts. Sometimes the pipe is fixed to a template on the seabed, which makes "Rotation" OFF the most realistic, but in most cases, the pipe is laid loose.

Displacement Vessel

Figure 6.27 and 6.28 illustrate how the vessel move during the analysis. The vessel moves in the same pattern for case 181 and 182. Case 181 moves further away from the laying route than case 182 which makes sense when the imperfection length is larger.

The vessel has to move quite rapidly from side to side to lay the pipe, which is not that realistic.

Algorithm

The laying algorithm in SIMLA makes the pipe node connect with the seabed node at the center of the seabed. The vessel is programmed to follow how the pipe move. When the imperfection reaches the seabed, the curved section will follow the center of the seabed, making the pipe move in a curved manner. This means that the vessel has to follow how the pipe behaves when the pipe starts to follow the same curve as the curved imperfection. It is then important to check that the pipe starts to rotate before the vessel starts to move.

Figure 6.29 shows a combined plot of how the vessel moves versus how the pipe rotates for each load step. By looking at the graph, it is clear that the rotation of the imperfection starts before the vessel starts to move.

When looking closely at case 182 in Figure 6.30, rotation of the pipe and the movement of the vessel start in the same order but are closer to each other.

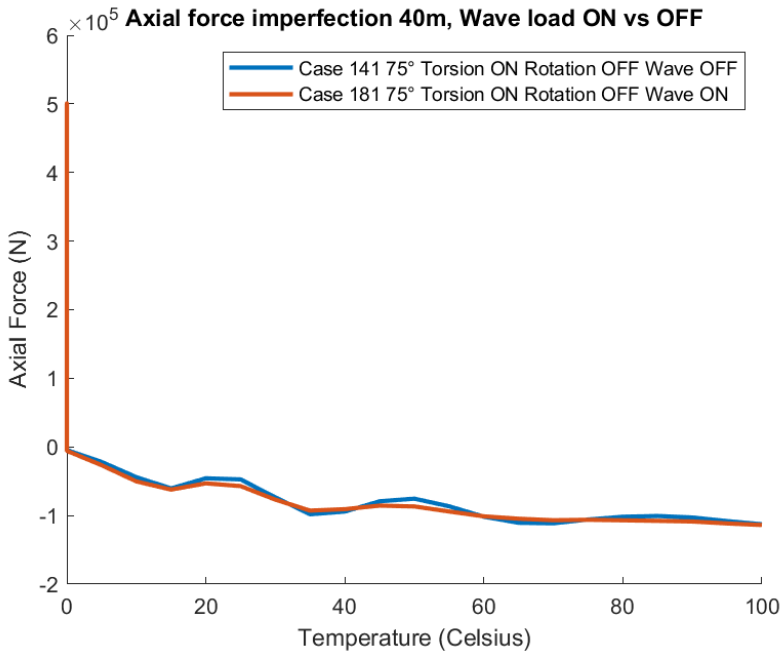


Figure 6.20: Axial force imperfection 40m, Wave vs no wave

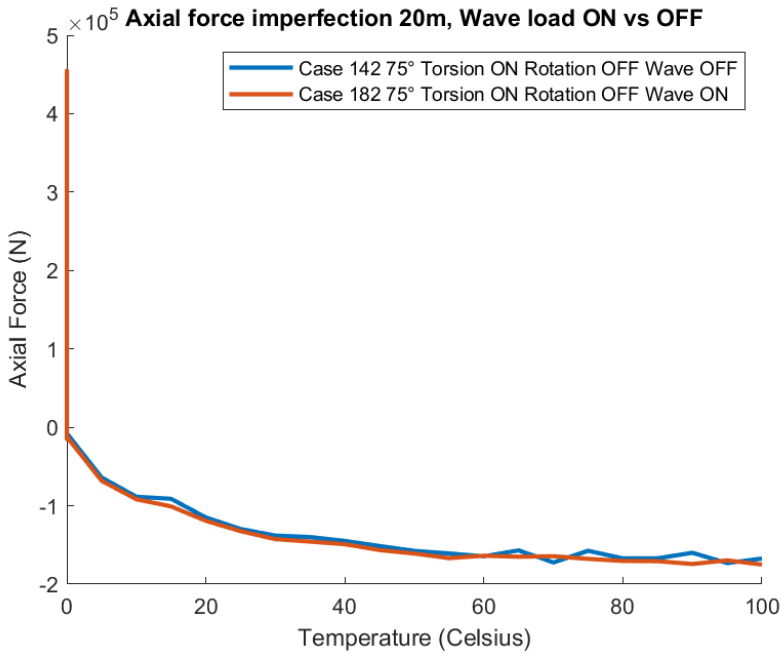


Figure 6.21: Axial force imperfection 20m, Wave vs no wave

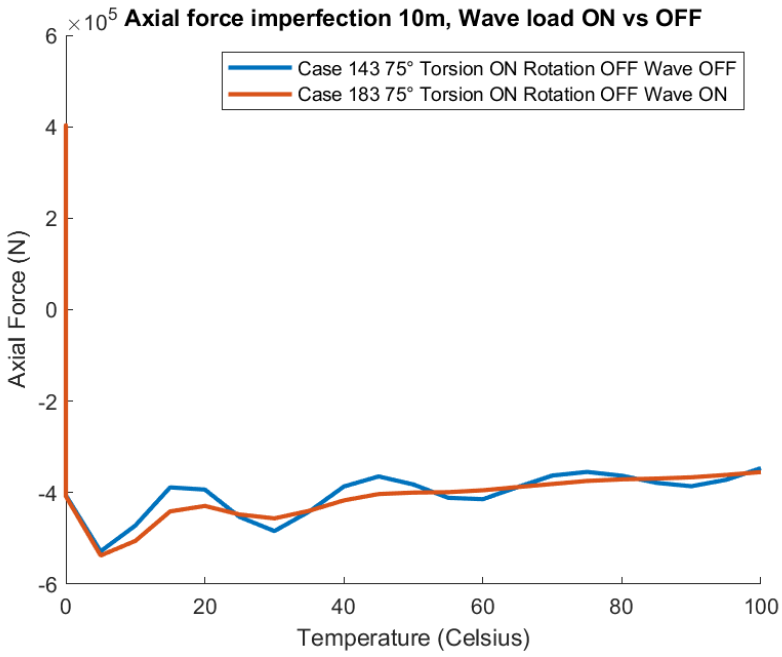


Figure 6.22: Axial force imperfection 10m, Wave vs no wave

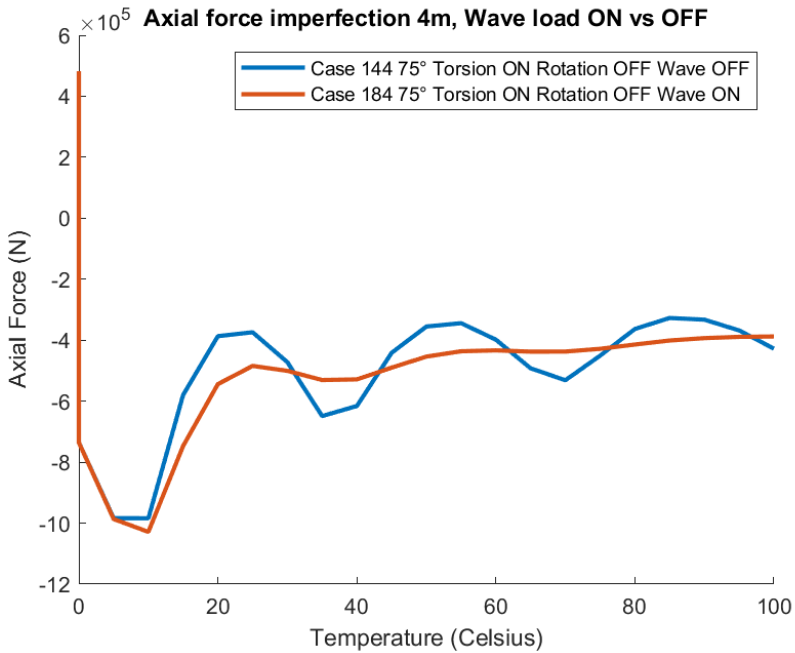


Figure 6.23: Axial force imperfection 4m, Wave vs no wave

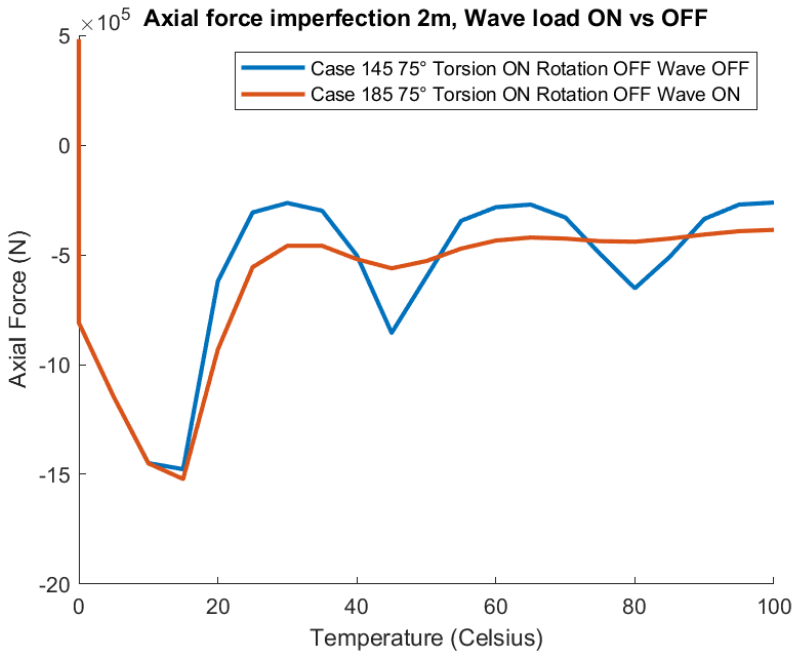


Figure 6.24: Axial force imperfection 2m, Wave vs no wave

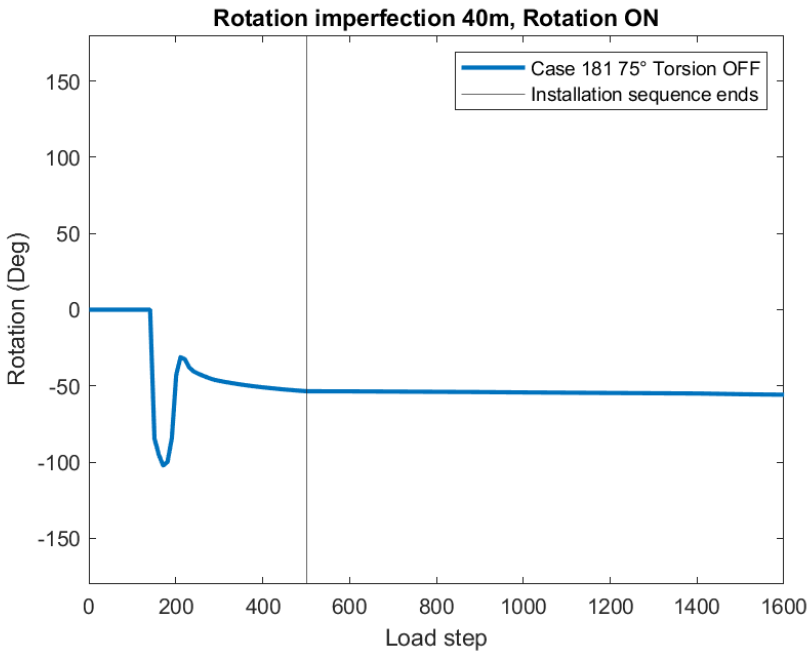


Figure 6.25: Rotation imperfection 40m

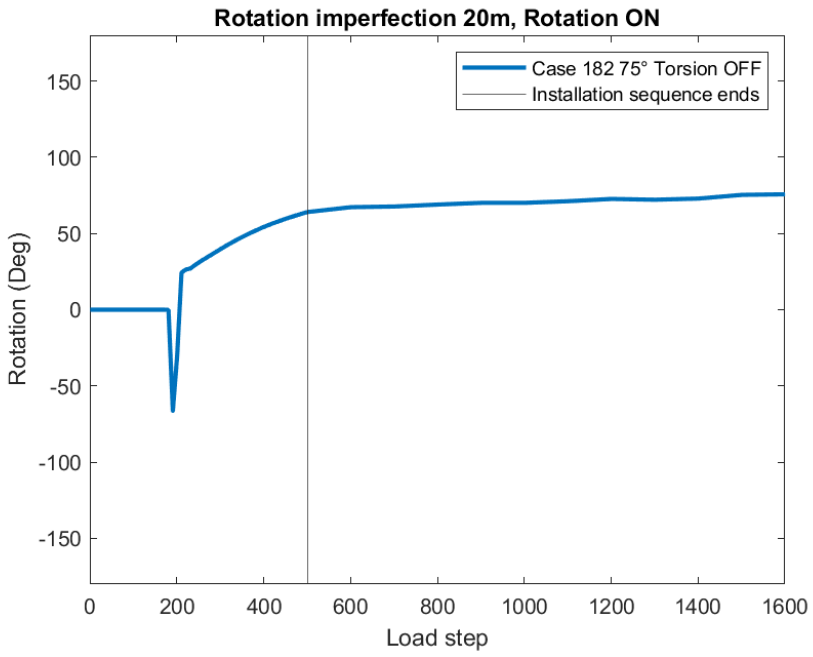


Figure 6.26: Rotation imperfection 20m

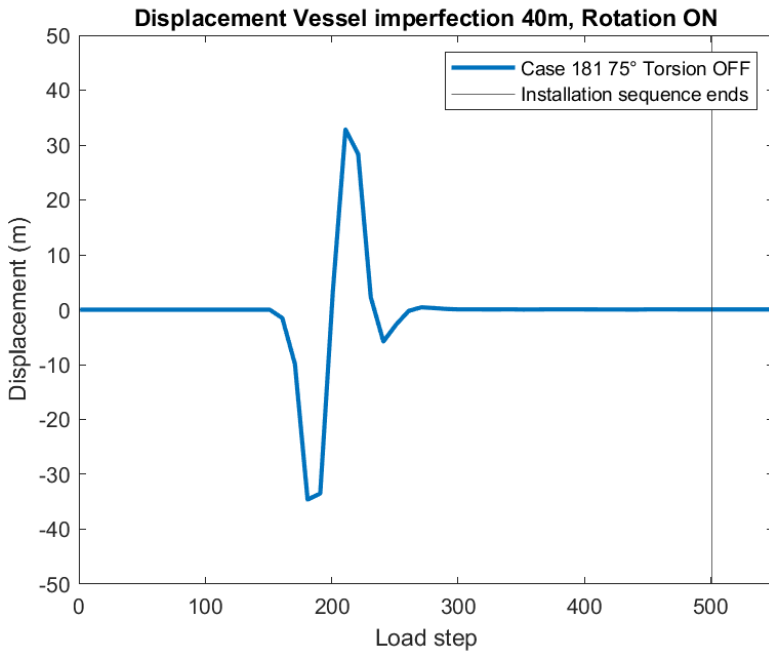


Figure 6.27: Displacement Vessel imperfection 40m

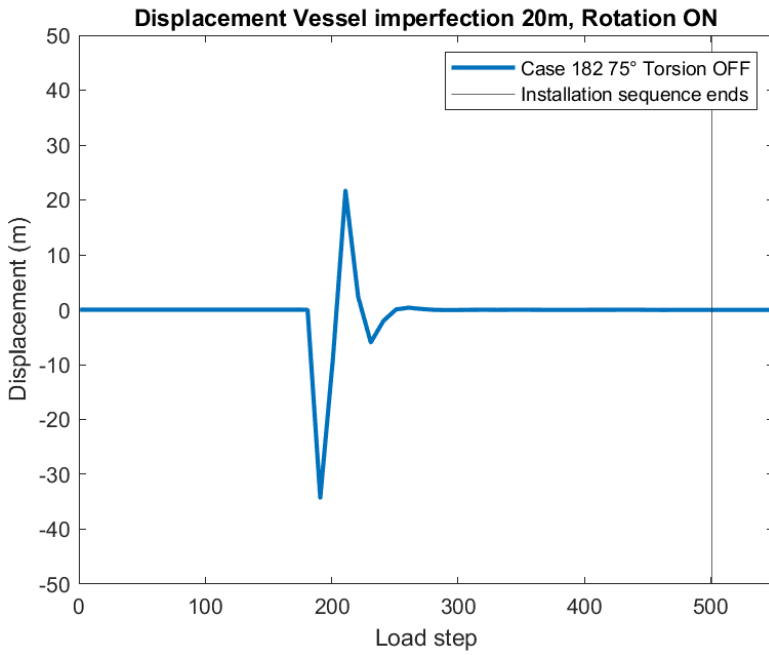


Figure 6.28: Displacement Vessel imperfection 20m

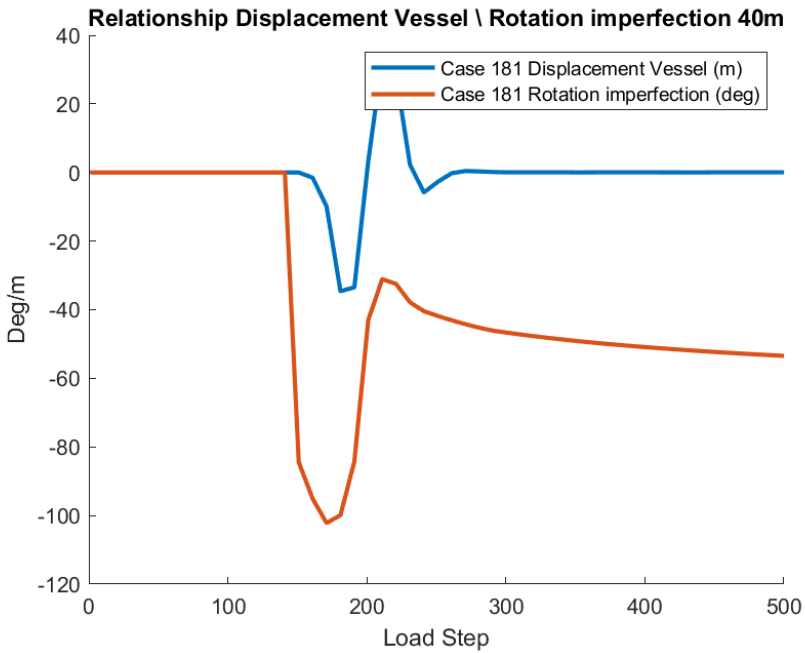


Figure 6.29: Displacement Vessel vs Rotation imperfection 40m

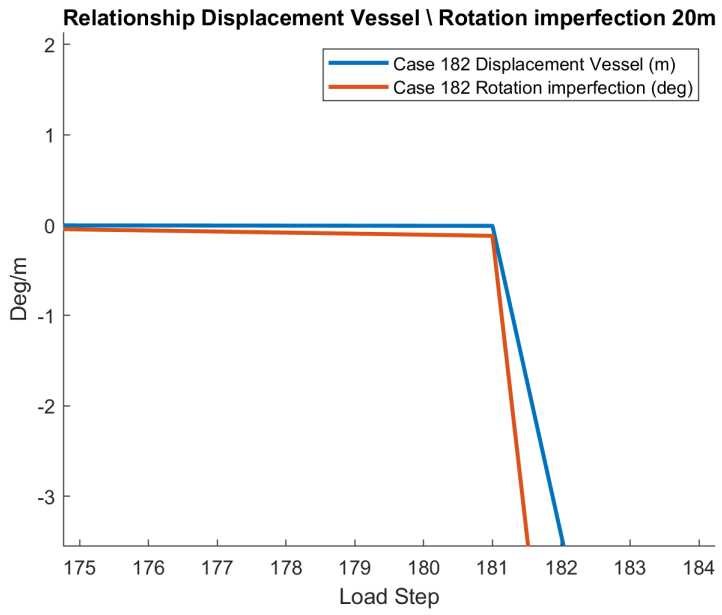


Figure 6.30: Displacement Vessel vs Rotation imperfection 20m closeup

6.6 Part 6 Parameter study

6.6.1 General

Explanation

In part 5, case 186, 188 and 189 failed. The results in Table 6.11 got the same configuration as the failed cases in part 5, which is the most conservative case with "Rotation" OFF, "Torsion" ON and departure angle of 75 degrees. It was essential to see what TSRP that is needed to make these cases converge. Therefore a sensitivity study was done concerning the TSRP.

Goal

The goal was to check if case 186, 188, and 189 from part 5 could converge by doing a sensitivity study by changing the TSRP.

6.6.2 Results

Table 6.11 list the results form part 6 of the parameter study. The range for the TSRP was set from 1.2 to 1.6 with a step increment of 0.2.

Case	Length	Torsion spring rotation parameter	Crit 1	Crit 1	Buckle	Rotation imp
191	40m	1.2	FAIL	FAIL	FAIL	FAIL
192	20m	1.2	70%	74%	VALID	NO
193	10m	1.2	FAIL	FAIL	FAIL	FAIL
194	4m	1.2	FAIL	FAIL	FAIL	FAIL
195	2m	1.2	56%	60%	PEAK	NO
196	40m	1.4	91%	95%	VALID	YES
197	20m	1.4	70%	74%	VALID	NO
198	10 m	1.4	FAIL	FAIL	FAIL	FAIL
199	4m	1.4	FAIL	FAIL	FAIL	FAIL
200	2m	1.4	56%	60%	PEAK	NO
201	40m	1.6	91%	95%	VALID	YES
202	20m	1.6	70%	74%	VALID	YES
203	10 m	1.6	FAIL	FAIL	FAIL	FAIL
204	4m	1.6	FAIL	FAIL	FAIL	FAIL
205	2m	1.6	56%	60%	PEAK	NO

Table 6.11: Results Part 6

6.6.3 Discussion

Torsion spring rotation parameter

Both 40m and 20m converge at a TSRP of 1.4. The configuration of all the cases in Table 6.11 is, as mentioned before, the most conservative. It is then crucial that this configuration converges. It is then clear that an imperfection length of 40m is safe to recommend as case 196

and 201 converges. With that said, the TSRP is quite high and needs to be considered carefully for further studies.

Imperfection Length

The results from all the parts in this chapter shows that the most robust imperfection length is 40m. At 40m, the imperfection always rotates if the case converges. Table 6.11 proves that the reason that an imperfection length of 40m FAILS is that the TSRP is too low.

It is also important to point out that an imperfection length of 20m is also a robust value. The reason for not picking 20m as the most optimal is that the case does not rotate in the most conservative configuration with "Rotation" OFF, and "Torsion" ON. These findings are significant and make an imperfection length of 40m preferable.

No matter what configuration, 4m, and 2m always peak if the cases converge. Imperfection length of 10m often fails and is quite unstable.

Rotation

Figure 6.31, 6.32 and 6.33 shows respectively the rotation of the imperfection in case 196, 201 and 202. Case 201 and 202 rotate the same, but case 196 rotates differently from the others. The only thing that divides them is the TSRP value. This proves that the analysis is susceptible to the TSRP value. The imperfection starts by rotating in the same manner but ends up lying down at the seabed on different sides.

The reason for this is that when the TSRP value is high, the torsion spring of the seabed gets very slack, making the rotation of the imperfection very sensitive. It is also important to point out that the imperfection rotates at 20m with a TSRP value of 1.6 but not at 1.4. This proves the instability of the TSRP.

To illustrate that the imperfection rotates as wanted, XPOST was used. Figure 6.34 shows that the imperfection has rotated and lies down on the seabed after the installation sequence. Figure 6.35 shows what it looks like when the imperfection does not rotate. This is a situation that is not wanted.

Buckle

Figure 6.36 shows that the imperfection in case 201 buckles in a controlled manner during the operation analysis. Figure 6.37 shows how case 197 buckles. It buckles in a controlled manner, but not in the right direction due to no rotation.

Displacement Vessel

The same difference explained for rotation is also shown concerning the displacement of the vessel. The deviation between cases 196 and 201 shown in Figure 6.38 and 6.39 is significant. The displacement in Figure 6.38 is quite unrealistic; no captain would move the laying vessel in the same manner as the graph shows. The steering algorithm discussed in part 5 is the reason for this. The installation tolerances concerning hitting the laying route at the seabed are quite strict.

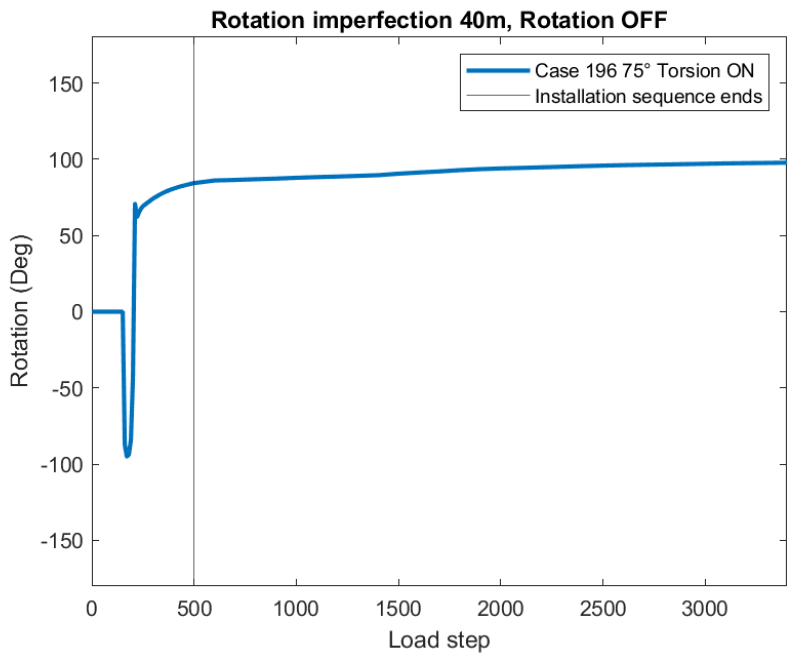


Figure 6.31: Rotation imperfection 40m

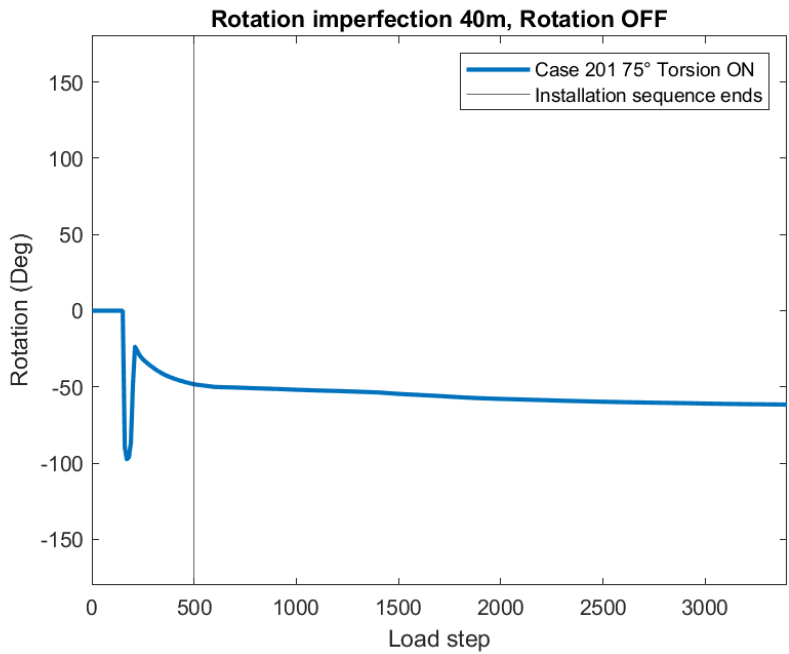


Figure 6.32: Rotation imperfection 40m

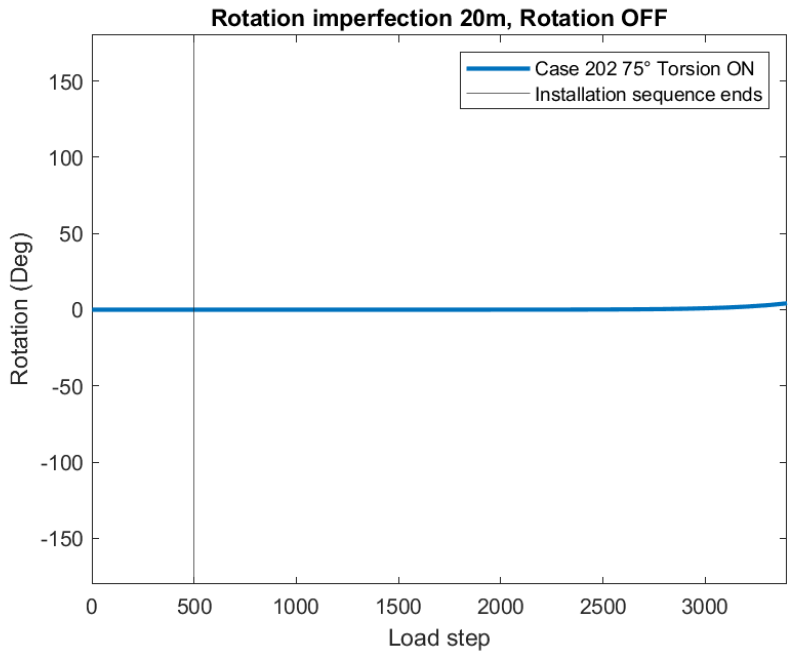


Figure 6.33: Rotation imperfection 20m

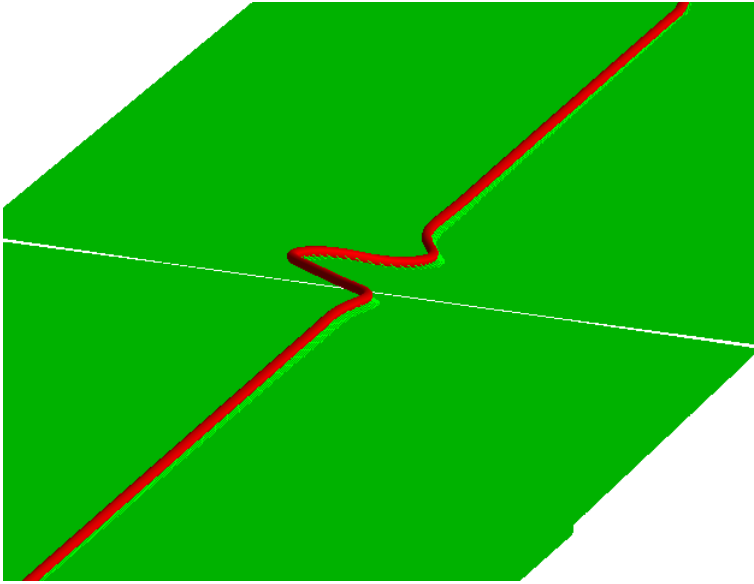


Figure 6.34: Rotation imperfection 40m XPOST

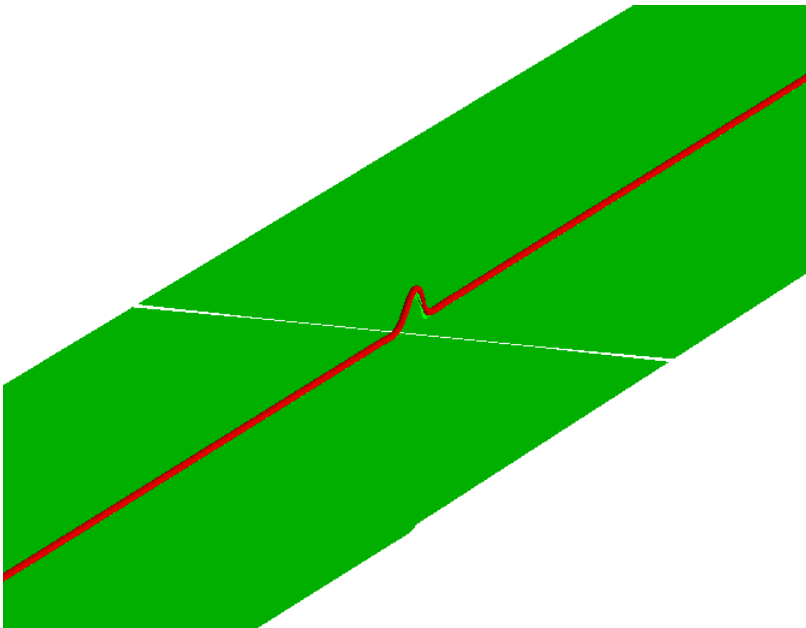


Figure 6.35: Rotation imperfection 40m XPOST

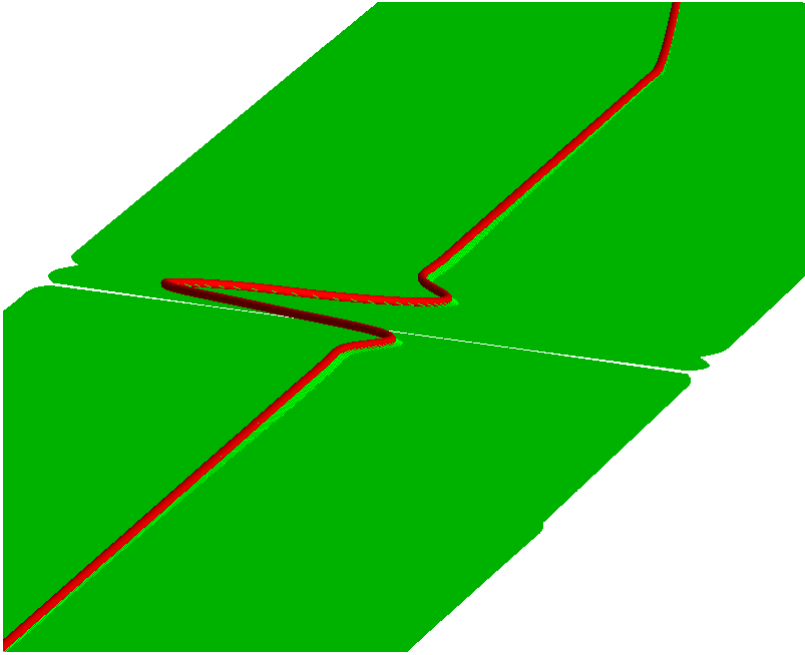


Figure 6.36: Buckle imperfection 40m XPOST

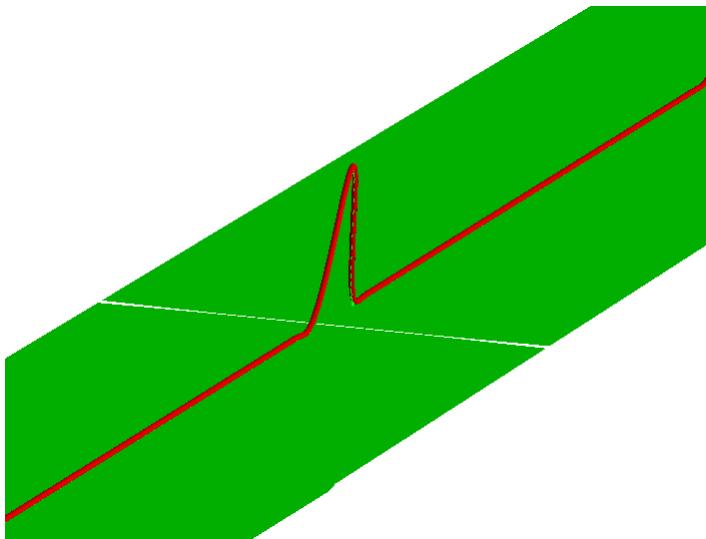


Figure 6.37: Buckle imperfection 20m XPOST

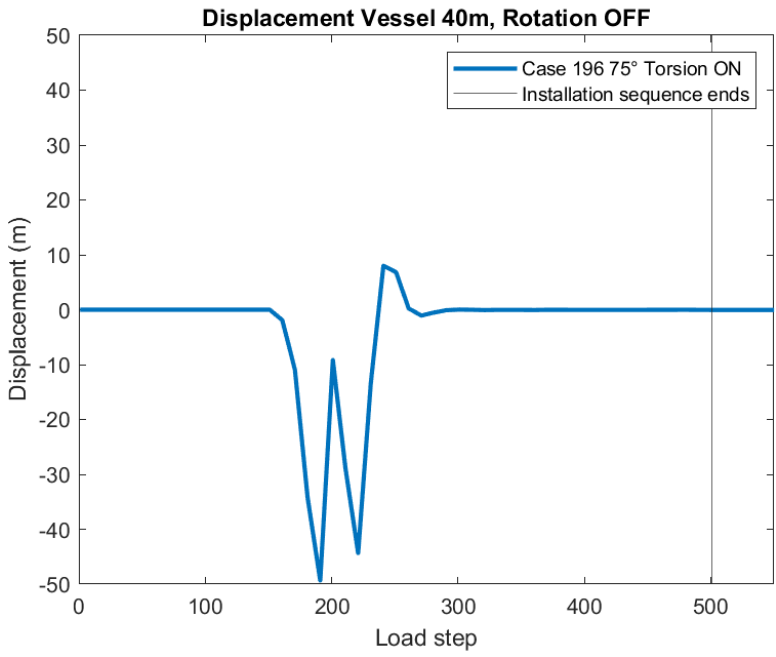


Figure 6.38: Displacement Vessel imperfection 40m

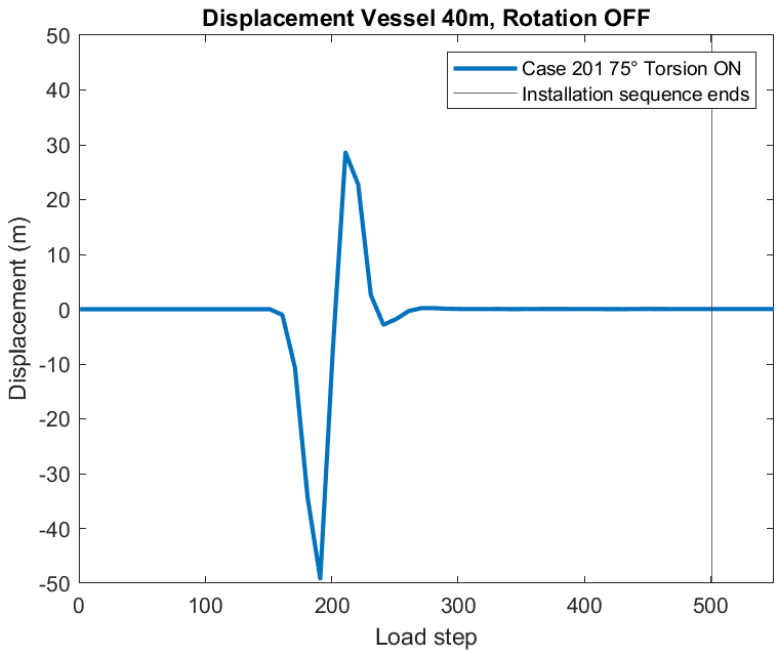


Figure 6.39: Displacement Vessel imperfection 40m

Conclusion

The purpose of this Thesis was to prove that the overall global buckling can be controlled at the initial phase of operation by introducing imperfections during the installation sequence.

7.1 Conclusion

Working Simla model that includes residual curvature has been proven to work as intended within the criteria described in the standard OF-F101. Imperfection length of 40m makes the imperfection rotate and buckle as wanted without any peak effect and is the optimal length for the laying scenario. Cases with imperfection length of 4m and 2m have a peak effect concerning the development in axial force and buckles in an uncontrolled manner. The development in axial force is different when the imperfection rotates. The max axial force is then lower compared to a case that does not rotate.

The wave load card has a damping effect on the axial force. The wave load card results in higher utilization of crit 1 and 2 for 4m and 2m imperfection length compared to no wave load card. The difference concerning the development of the axial force when including the wave load card versus not including it is higher for shorter imperfection lengths. The change in departure angle (70,75 and 80 degrees) has almost no effect concerning the utilization of crit 1, and 2. Residual curvature of 0.015 is proven to be the most robust value to use in a parameter study. The development in crit 1 and 2 versus the imperfection length with different residual curvature values do not follow the same trend.

In summary, these findings prove that it is safe to lay a pipeline at 380m water depth with an imperfection length of 40m with departure 70, 75, or 80 degrees. The main goal of controlling global buckling by installing prebent sections is achieved.

The laying algorithm installation tolerances are strict and do not describe how the vessel will move during the installation sequence. In real life, the tolerances to move the pipe outside the theoretical laying route will be larger.

7.2 Recommendations for further work

Optimizing the laying algorithm concerning installation tolerances should be studied. The reason is that this is sometimes the limiting factor concerning making the analysis converge

Change in water depth should also be studied. The water depth in this Thesis is set as constant 380m and does not give a full picture of how the change in depth affects the analysis. It will also be interesting to do a parameter study with a seabed that varies the topology.

To implement more buckles in the pipeline configuration and calculate the distance between the imperfections as described in RP-F110, needs to be done for further studies. How the axial force develop with a configuration with more than one imperfection is an interesting problem to analyze

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Appendix

A Calculations SIMLA

Outer diameter pipe

$$Odp = t_{steel}2 + ID + t_{coat}2 \quad (1)$$

$$Odp = 0.025m + 0.3556m + 0.07485m * 2 = 0.5552m$$

Outer diameter steel

$$Opd_{Steel} = ID + t_{steel}2 = 0.3556m + 0.025m * 2 = 0.4056m \quad (2)$$

Cross section area steel

$$Area_{Steel} = \pi \frac{OD_{Steel}^2 - ID_{Steel}^2}{4} \quad (3)$$

$$Area_{Steel} = \pi \frac{0.4056m^2 - 0.3556m^2}{4} = 0.02989m^2$$

Mean radius

$$rad = \frac{ID + 2cladding + t_{steel}}{2} \quad (4)$$

$$rad = \frac{0.3556m + 20.003m + 0.022m}{2} = 0.1918m$$

Dry Mass

$$wd = \text{Density material} * \text{Cross section Area} \quad (5)$$

$$wd = \rho_{Steel}A_{Steel} + \rho_{coating}A_{Coating}$$

$$wd = 7850 \frac{Kg}{m^3} 0.02989m^2 + 769 \frac{Kg}{m^3} \pi \frac{(0.5552^2m - 0.4056m^2)}{4}$$

$$wd = 234.63 \frac{Kg}{m} + 86.81 \frac{Kg}{m} = 321 \frac{Kg}{m}$$

Buoyancy Mass

$$wb = \text{Displaced Volume} * \text{Density Seawater} \quad (6)$$

$$W_b = \frac{\pi d^2 \rho_{Seawater}}{4}$$

$$W_b = \frac{\pi 0.5552m^2 * 1026 \frac{Kg}{m^3}}{4} = 248 \frac{Kg}{m}$$

Submerged Mass

$$W_s = wd - wb = 321 \frac{Kg}{m} - 248 \frac{Kg}{m} = 73 \frac{Kg}{m} \quad (7)$$

Axial Stiffness

$$E_a = E - module * Area_{Steel} \quad (8)$$

$$E_a = 210 * 10^9 \frac{Kg}{m.s^2} * 0.02989m = 6.27 * 10^9 N$$

Bending Stiffness

$$EI = EI_y = EI_z = E\text{-module} * \text{Second moment of inertia} \quad (9)$$

$$EI = 210 * 10^9 \frac{Kg}{m.s^2} * \pi \frac{(0.4056m^4 - 0.3556N^4)}{64} = 1.14 * 10^8 Nm^2$$

Torsion Stiffness

$$G_{it} = \text{Shear modulus} * \text{Polar moment of inertia} \quad (10)$$

$$G_{it} = 79.3 * 10^9 \frac{N}{m^2} \pi \frac{(0.4056m^4 - 0.3556m^4)}{32} = 8.62 * 10^7 Nm^2$$

Youngs modulus

$$Em = \text{Youngs modulus} = 210 * 10^9 \frac{N}{m^2} \quad (11)$$

Shear modulus

$$Gm = \text{Shear modulus} = 79.3 * 10^9 \frac{N}{m^2} \quad (12)$$

B Calculations Local Buckling

B.1 Installation

Design criteria 1

$$\left\{ \gamma_m * \gamma_{SC} * \frac{|M_{Sd}|}{\alpha_c * M_p} + \left\{ \frac{\gamma_m * \gamma_{SC} * S_{Sd}}{\alpha_c * S_p} \right\}^2 \right\}^2 + \left(\gamma_m * \gamma_{SC} * \frac{P_e - P_{min}}{P_c} \right)^2 \leq 1 \quad (13)$$

Applies for

$$15 \leq \frac{D}{t} \leq 45 \quad (14)$$

$$P_i < P_e \quad (15)$$

$$\frac{|S_{Sd}|}{S_p} < 0.4 \quad (16)$$

Description	Unit	Value	Reference
Load effect factor	γ_F	1.2	Table 4-4 DNV OS-F101
Condition load effect factor	γ_C	1.0	Table 4-5 DNV OS-F101
Material resistance factor	γ_m	1.15	Table 5-2 DNV OS-F101
Safety class resistance factor	γ_{SC}	1.04	Table 5-3 DNV OS-F101
Material Strength factor	α_U	0.96	Table 5-4 DNV OS-F101
Maximum Fabrication factor	α_{fab}	0.93	Table 5-5 DNV OS-F101
Yield Stress	SMYS	448 MPa	Table 13-4 DNV OS-F101
Tensile Strength	SMTS	530 Mpa	Table 13-4 DNV OS-F101
Ovality	f_o	0.005	Equation 5.14 DNVGL OS-F101
Minimum internal pressure	p_{min}	0	Empty Pipe
Characteristic internal pressure	p_i	0	Empty Pipe
De-rating Yield Stress	$f_{y,temp}$	0	No temp under Installation
De-rating Tensile Strength	$f_{u,temp}$	0	No temp under Installation
Water depth	h	380 m	
Gravity	g	9.81 $\frac{m}{s^2}$	
Water density	ρ_{Sw}	1026 $\frac{Kg}{m^3}$	
Poisson ratio	ν	0.3	

Table 1: Buckling Data Installation

Characteristic material strength

$$f_y = (SMYS - f_{y,temp})\alpha_U \quad f_y = 4.3008 * 10^8 Pa \quad (17)$$

$$f_u = (SMTS - f_{u,temp})\alpha_U \quad f_u = 5.088 * 10^8 Pa \quad (18)$$

Plastic moment capacity

$$M_p = f_y(D - t)^2 t \quad M_p = 2.69 * 10^6 J \quad (19)$$

Design Moment

$$M_{Sd} = M_F \gamma_F \gamma_C + M_E \gamma_E + M_I \gamma_F \gamma_C + M_A \gamma_A \gamma_C \quad M_{Sd} = 2.261 * 10^6 Nm \quad (20)$$

Plastic axial tension capacity

$$S_p = f_y \pi (D - t) t \quad S_p = 1.0 * 10^{14} N \quad (21)$$

Design Axial tension

$$S_{Sd} = S_F * \gamma_F * \gamma_C + S_E * \gamma_E + S_I * \gamma_F * \gamma_C + S_A * \gamma_A * \gamma_C \quad S_{Sd} = 6.021 * 10^5 N \quad (22)$$

Combined loading factor

$$\beta = \frac{60 - \frac{D}{t}}{90} \quad \beta = 0.3863 \quad (23)$$

Flow stress parameter

$$\alpha_C = (1 - \beta) + \beta \frac{f_u}{f_y} \quad \alpha_c = 1.0707 \quad (24)$$

External pressure

$$P_e = \rho_{Sw} g h \quad P_e = 3.8 * 10^6 Pa \quad (25)$$

Resistance for external pressure

$$(P_c - P_{el})(P_c^2 - P_p^2) = P_c P_{el} P_p f_0 * \frac{D}{t} \quad (26)$$

Elastic Collapse pressure

$$P_{el} = f_y \alpha_{fab} \frac{2t}{D} \quad P_{el} = 2.8 * 10^7 \quad (27)$$

Plastic Collapse pressure

$$P_P = f_y \alpha_{fab} \frac{2t}{D} \quad P_P = 3.17 * 10^7 \quad (28)$$

Pressure Collapse

Solving the third degree polynomial with respect to P_c . The analytical solution is calculated according to DNVGL OS-F101 equation 13.13

$$P_c = y - \frac{1}{3}b \quad (29)$$

$$b = -P_{el} \qquad b = -2.87 * 10^7$$

$$c = - \left(P_p^2 + P_p P_{el} f_0 \frac{D}{t} \right) \qquad c = -1.1 * 10^{15}$$

$$d = P_{el} P_p^2 \qquad d = 2.8 * 10^{22}$$

$$u = \frac{1}{3} \left(-\frac{1}{3}b^2 + c \right) \qquad u = -4.6 * 10^{14}$$

$$v = \frac{1}{2} \left(\frac{2}{27}b^3 - \frac{1}{3}bc + d \right) \qquad v = 8.19 * 10^{21}$$

$$\Phi = \cos^{-1} \left(\frac{-v}{\sqrt{-u^3}} \right) \qquad \Phi = 2.52$$

$$y = \sqrt{-u} \cos \left(\frac{\Phi}{3} + \frac{60\pi}{180} \right) \qquad y = 1.3 * 10^7$$

$$P_c = -2.7 * 10^7 Pa$$

Design criteria 1

$$\left\{ \gamma_m \gamma_{SC} \frac{|M_{Sd}|}{\alpha_c M_p} + \left\{ \frac{\gamma_m \gamma_{SC} S_{Sd}}{\alpha_c S_p} \right\}^2 \right\}^2 + \left(\gamma_m \gamma_{SC} \frac{P_e - P_{min}}{P_c} \right)^2 = 0.91 \Rightarrow OK \quad (30)$$

Applies for

$$15 \leq \frac{D}{t} \leq 45 = 25.2364 \Rightarrow OK \quad (31)$$

$$P_i < P_e = P_i = 0 \Rightarrow OK \quad (32)$$

$$\frac{|S_{Sd}|}{S_p} = 6 * 10^{-9} \Rightarrow OK \quad (33)$$

B.2 Operation

Design criteria 2

$$\left\{ \gamma_m * \gamma_{SC} * \frac{|M_{Sd}|}{\alpha_c * M_p} + \left\{ \frac{\gamma_m * \gamma_{SC} * S_{Sd}}{\alpha_c * S_p} \right\}^2 \right\}^2 + \left(\alpha_p * \frac{P_i - P_e}{\alpha_c * P_b} \right)^2 \leq 1 \quad (34)$$

Applies for

$$15 \leq \frac{D}{t} \leq 45 \quad (35)$$

$$P_i > P_e \quad (36)$$

$$\frac{|S_{Sd}|}{S_p} < 0.4 \quad (37)$$

Description	Unit	Value	Reference
Load effect factor factor	γ_F	1.2	Table 4-4 DNV OS-F101
Condition load effect factor	γ_C	1.0	Table 4-5 DNV OS-F101
Material resistance factor	γ_m	1.15	Table 5-2 DNV OS-F101
Safety class resistance factor	γ_{SC}	1.04	Table 5-3 DNV OS-F101
Material Strength factor	α_U	0.96	Table 5-4 DNV OS-F101
Maximum Fabrication factor	α_{fab}	0.93	Table 5-5 DNV OS-F101
Yield Stress	SMYS	448 MPa	Table 13-4 DNV OS-F101
Tensile Strength	SMTS	530 Mpa	Table 13-4 DNV OS-F101
Ovality	f_o	0.005	Equation 5.14 DNVGL OS-F101
Minimum internal pressure	p_{min}	0	
Characteristic internal pressure	p_i	20 MPa	Operation pressure
De-rating Yield Stress	$f_{y,temp}$	30 MPa	C300 Figure 2 DNV OS-F101
De-rating Tensile Strength	$f_{u,temp}$	30 Mpa	C300 Figure 2 DNV OS-F101
Water depth	h	380 m	
Gravity	g	$9.81 \frac{m}{s^2}$	
Water density	ρ_{Sw}	$1026 \frac{Kg}{m^3}$	
Poisson ratio	ν	0.3	

Table 2: Buckling Data Operation

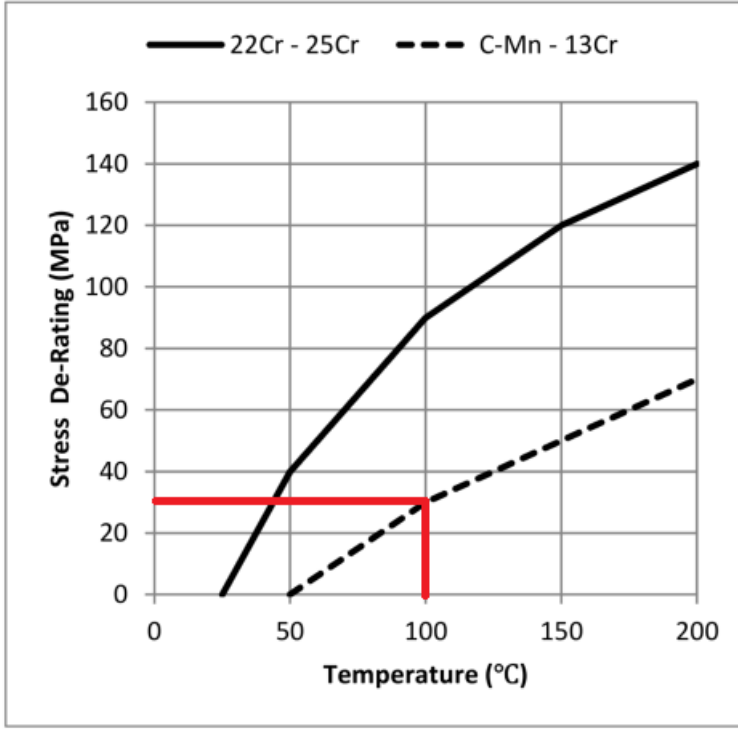


Figure 1: De-rating values for operation

Characteristic material strength

$$f_y = (SMYS - f_{y,temp})\alpha_U \quad f_y = 4.3008 * 10^8 Pa \quad (38)$$

$$f_u = (SMTS - f_{u,temp})\alpha_U \quad f_u = 5.088 * 10^8 Pa \quad (39)$$

Plastic moment capacity

$$M_p = f_y(D - t)^2 t \quad M_p = 2.69 * 10^6 J \quad (40)$$

Design Moment

$$M_{Sd} = M_F\gamma_F\gamma_C + M_E\gamma_E + M_I\gamma_F\gamma_C + M_A\gamma_A\gamma_C \quad M_{Sd} = 2.261 * 10^6 Nm \quad (41)$$

Plastic axial tension capacity

$$S_p = f_y\pi(D - t)t \quad S_p = 1.00 * 10^{14} N \quad (42)$$

Design Axial tension

$$S_{Sd} = S_{F\gamma F\gamma C} + S_{E\gamma E} + S_{I\gamma F\gamma C} + S_{A\gamma A\gamma C} \quad S_{Sd} = 6.0 * 10^5 N \quad (43)$$

Combined loading factor

$$\beta = \frac{60 - \frac{D}{t}}{90} \quad \beta = 0.3863 \quad (44)$$

Flow stress parameter

$$\alpha_C = (1 - \beta) + \beta \frac{f_u}{f_y} \quad \alpha_c = 1.0707 \quad (45)$$

External pressure

$$P_e = \rho_{Sw}gh \quad P_e = 3.8 * 10^6 Pa \quad (46)$$

Resistance for external pressure

$$(P_c - P_{el})(P_c^2 - P_p^2) = P_c P_{el} P_p f_0 * \frac{D}{t} \quad (47)$$

Elastic Collapse pressure

$$P_{el} = f_y \alpha_{fab} \frac{2t}{D} \quad P_{el} = 2.8 * 10^7 \quad (48)$$

Plastic Collapse pressure

$$P_P = f_y \alpha_{fab} \frac{2t}{D} \quad P_P = 3.17 * 10^7 \quad (49)$$

Pressure Collapse Pressure

Solving the third degree polynomial with respect to P_c . The analytical solution is calculated according to DNVGL OS-F101 equation 13.13

$$P_c = y - \frac{1}{3}b \quad (50)$$

$$b = -P_{el} \qquad b = -2.87 * 10^7$$

$$c = - \left(P_p^2 + P_p P_{el} f_0 \frac{D}{t} \right) \qquad c = -1.1 * 10^{15}$$

$$d = P_{el} P_p^2 \qquad d = 2.8 * 10^{22}$$

$$u = \frac{1}{3} \left(-\frac{1}{3} b^2 + c \right) \qquad u = -4.6 * 10^{14}$$

$$v = \frac{1}{2} \left(\frac{2}{27} b^3 - \frac{1}{3} bc + d \right) \qquad v = 8.19 * 10^{21}$$

$$\Phi = \cos^{-1} \left(\frac{-v}{\sqrt{-u^3}} \right) \qquad \Phi = 2.52$$

$$y = \sqrt{-u} \cos \left(\frac{\Phi}{3} + \frac{60\pi}{180} \right) \qquad y = -3.66 * 10^7$$

$$P_c = 2.7 * 10^7 Pa$$

Design criteria 2

$$\left\{ \gamma_m * \gamma_{SC} * \frac{|M_{Sd}|}{\alpha_c * M_p} + \left\{ \frac{\gamma_m * \gamma_{SC} * S_{Sd}}{\alpha_c * S_p} \right\}^2 \right\}^2 + \left(\gamma_m * \gamma_{SC} * \frac{P_e - P_{min}}{P_c} \right)^2 = 0.95 \Rightarrow \quad OK \quad (51)$$

Applies for

$$15 \leq \frac{D}{t} \leq 45 = 25.2364 \Rightarrow \quad OK \quad (52)$$

$$P_i > P_e = P_i = 20 MPa > 3.8 MPa \Rightarrow \quad OK \quad (53)$$

$$\frac{|S_{Sd}|}{S_p} = 0.6 * 10^{-9} \Rightarrow \quad OK \quad (54)$$

C Plot results

C.1 Axial force

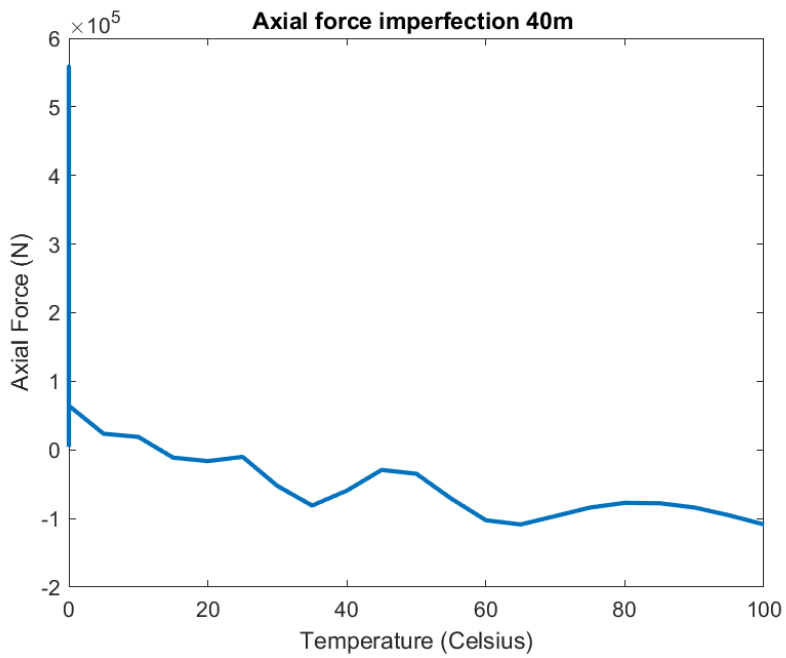


Figure 2: Axial force case 91

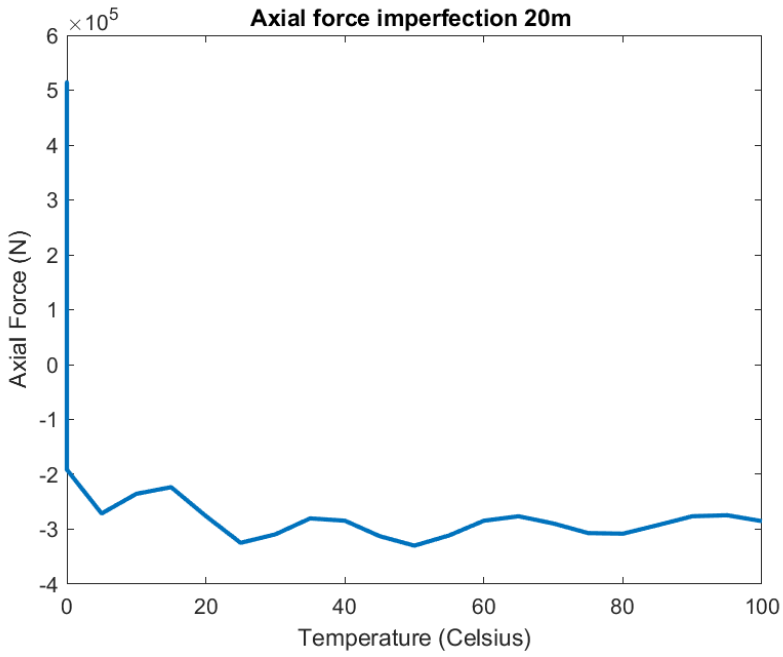


Figure 3: Axial force case 92

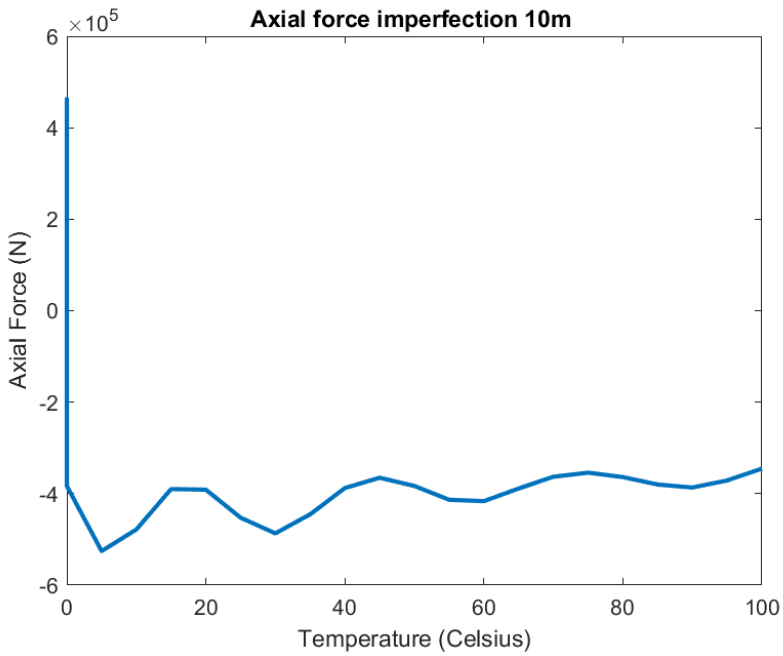


Figure 4: Axial force case 93

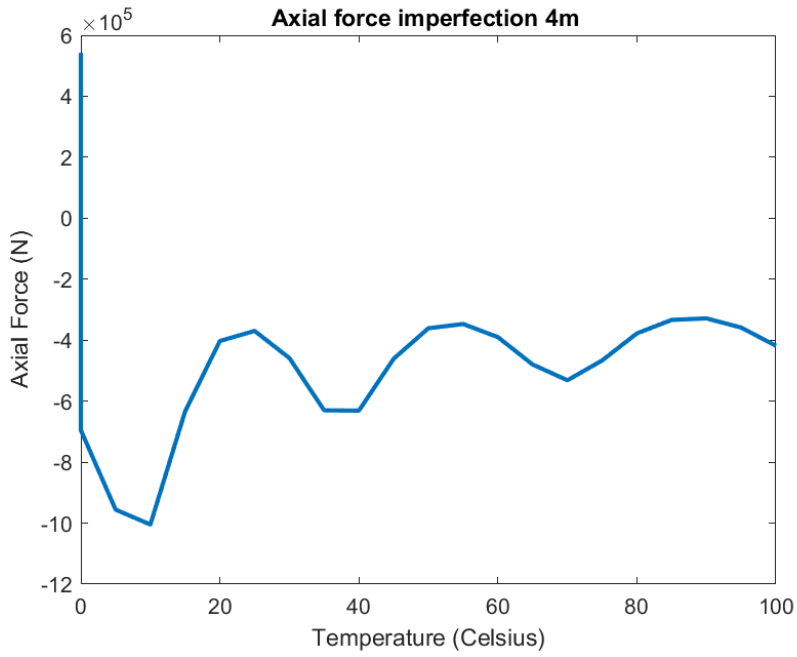


Figure 5: Axial force case 94

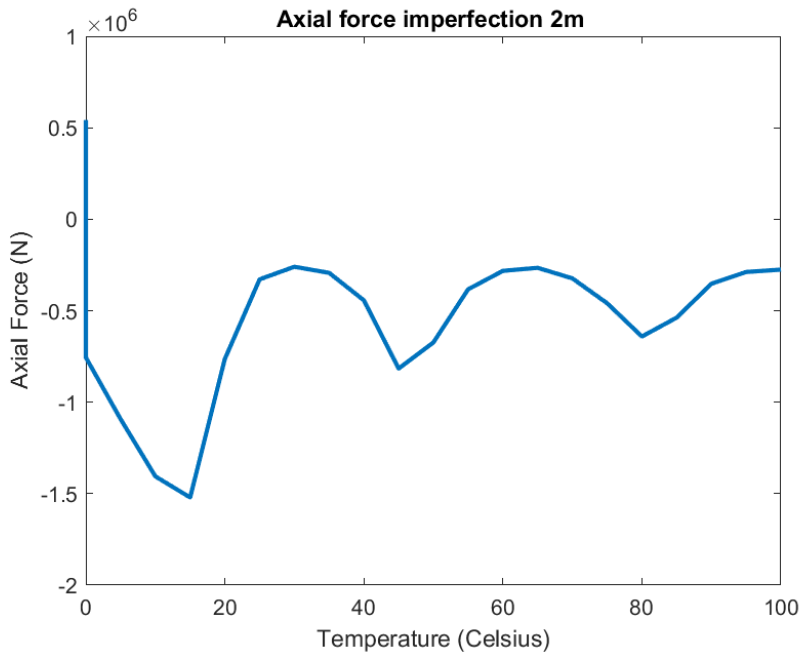


Figure 6: Axial force case 95

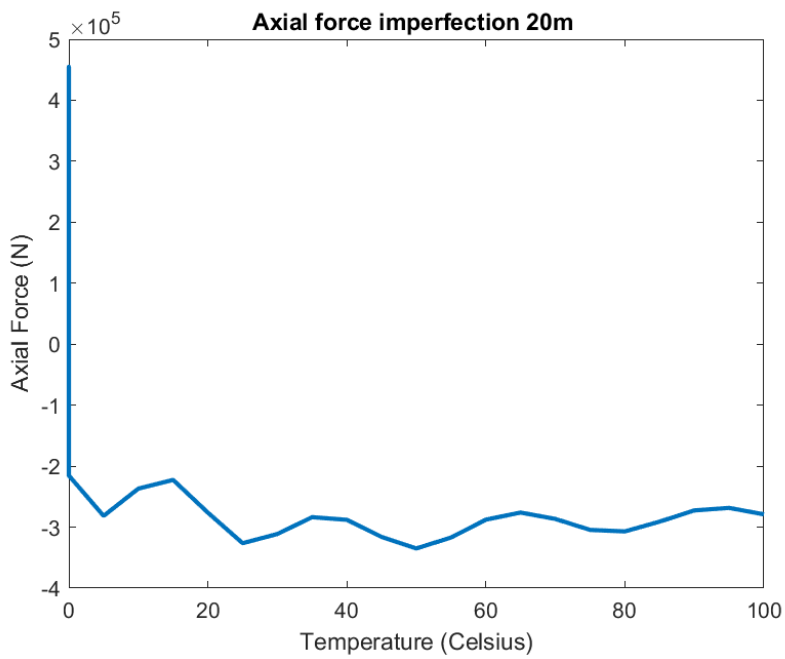


Figure 7: Axial force case 97

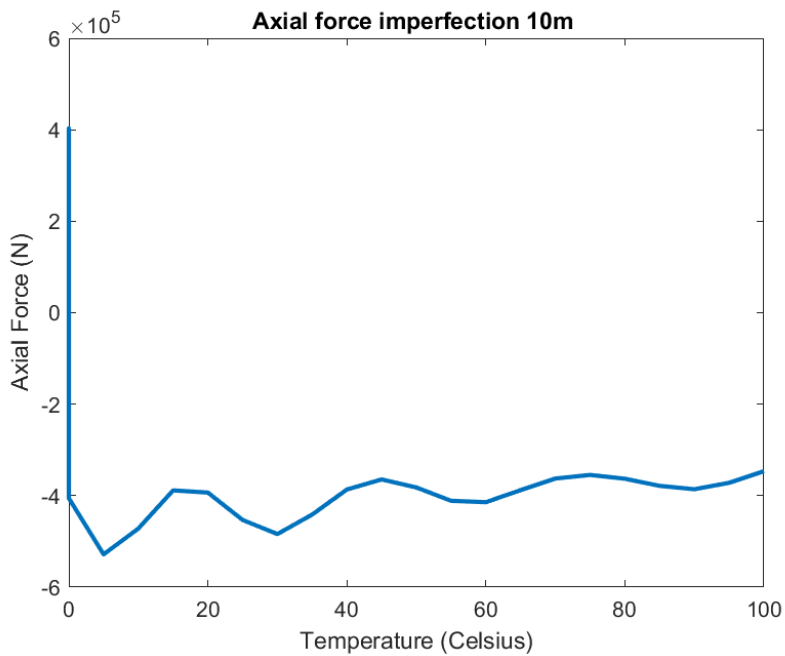


Figure 8: Axial force case 98

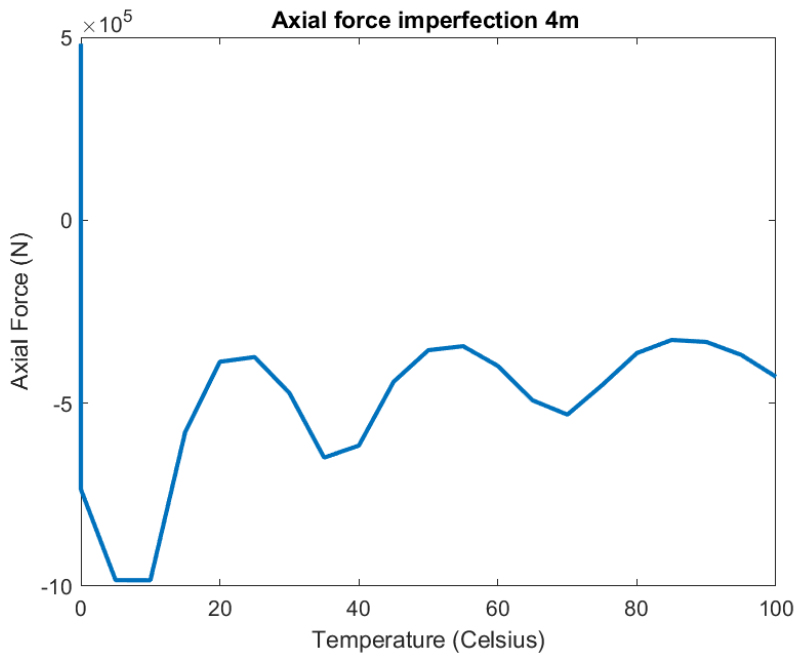


Figure 9: Axial force case 99

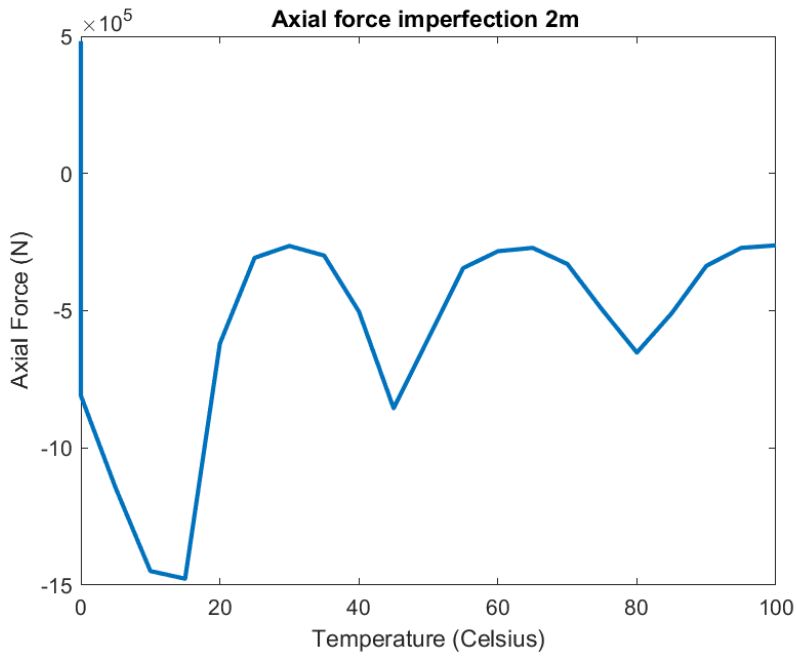


Figure 10: Axial force case 100

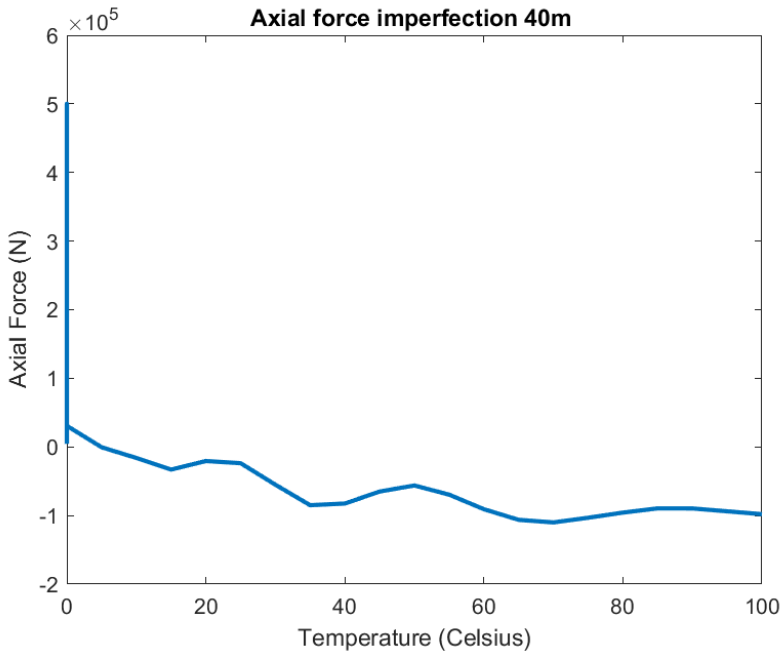


Figure 11: Axial force case 101

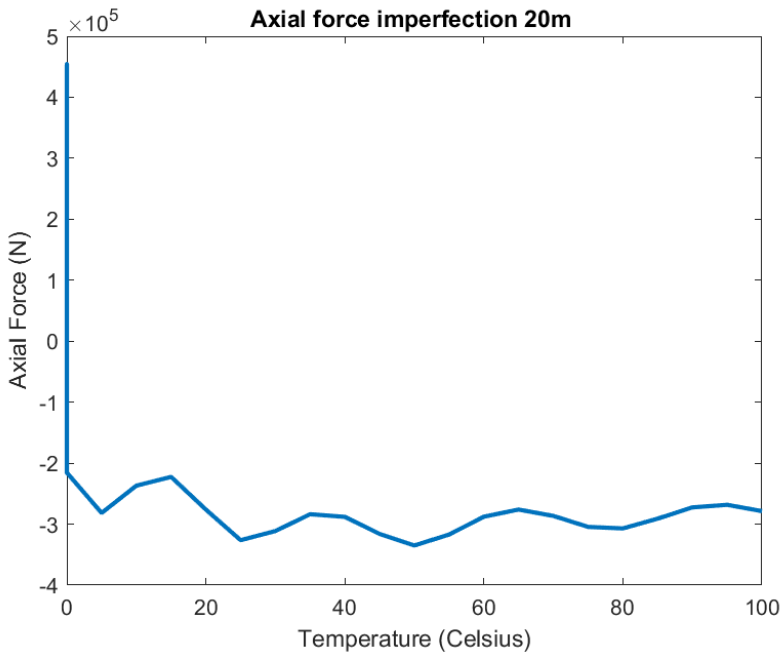


Figure 12: Axial force case 102

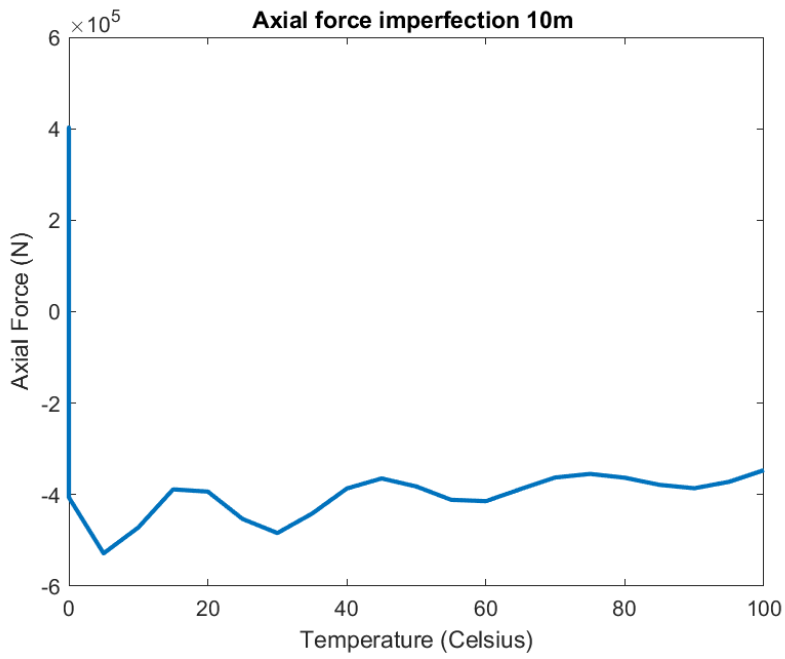


Figure 13: Axial force case 103

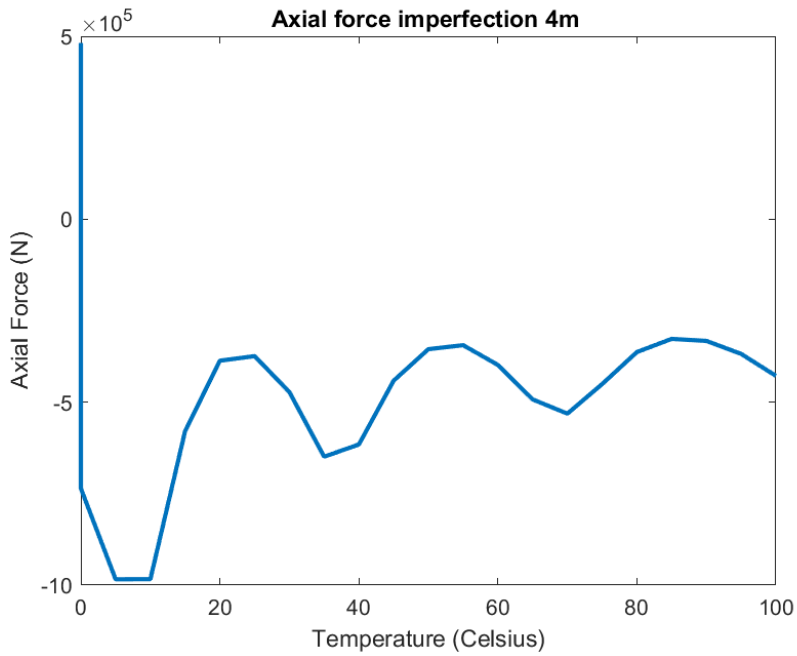


Figure 14: Axial force case 104

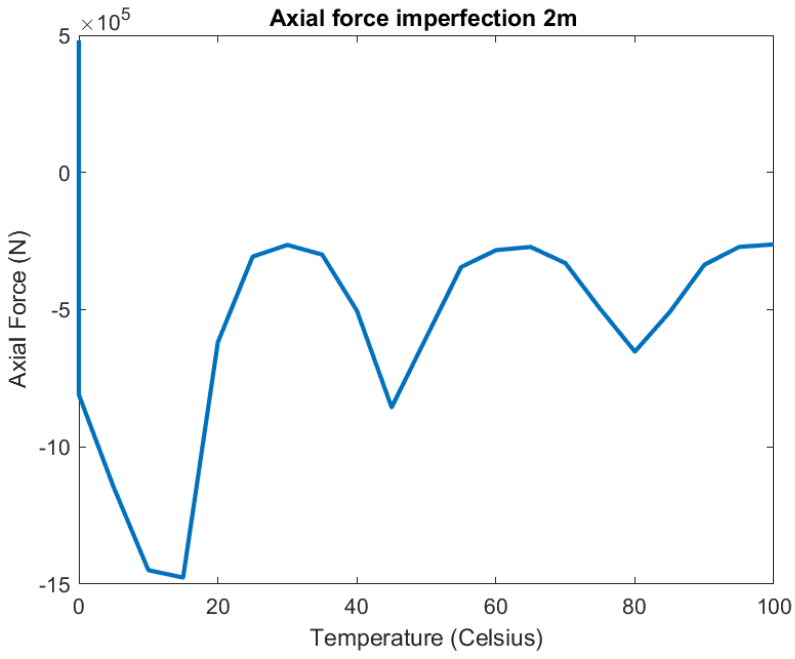


Figure 15: Axial force case 105

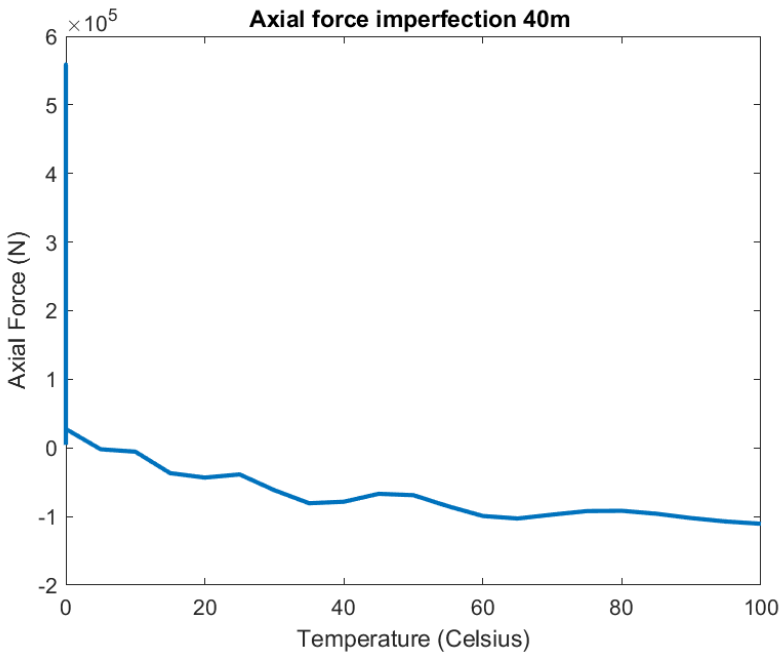


Figure 16: Axial force case 106

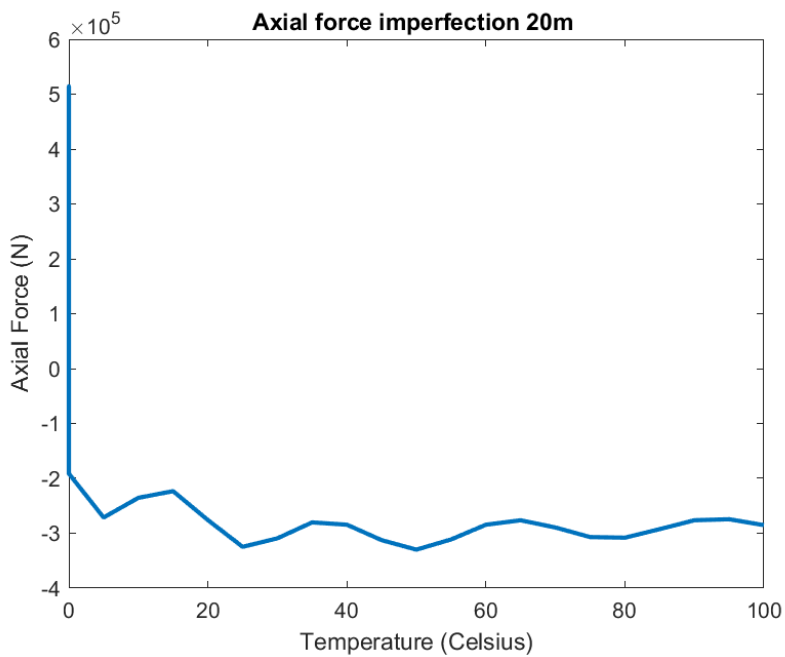


Figure 17: Axial force case 107

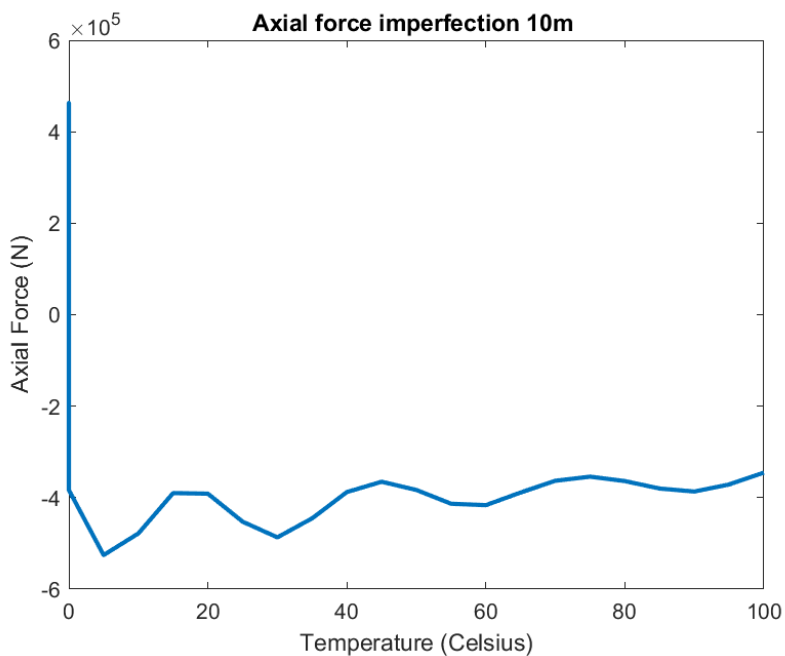


Figure 18: Axial force case 108

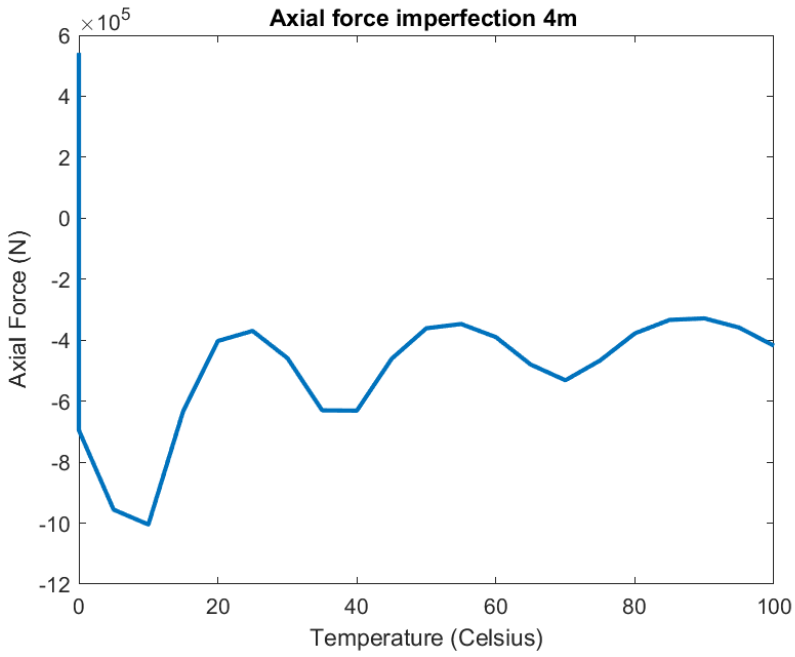


Figure 19: Axial force case 109

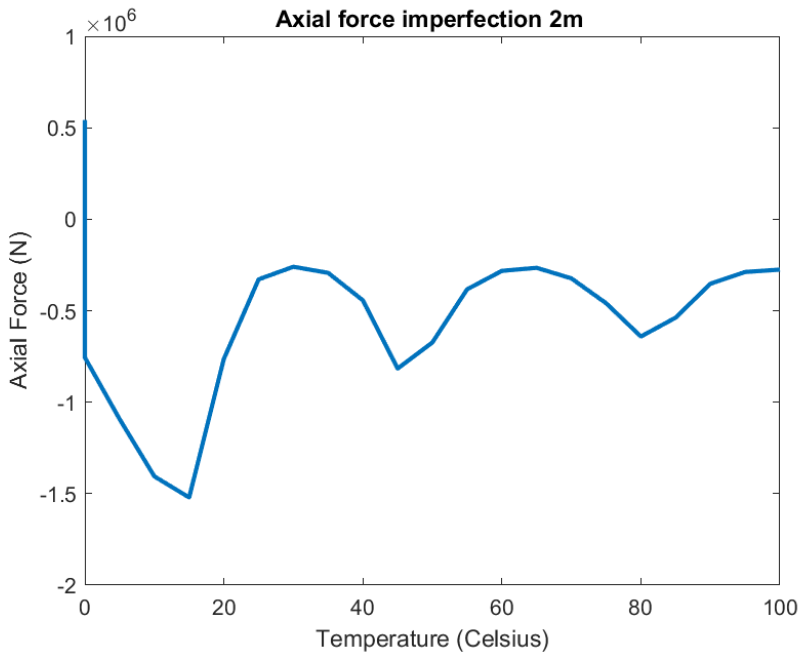


Figure 20: Axial force case 110

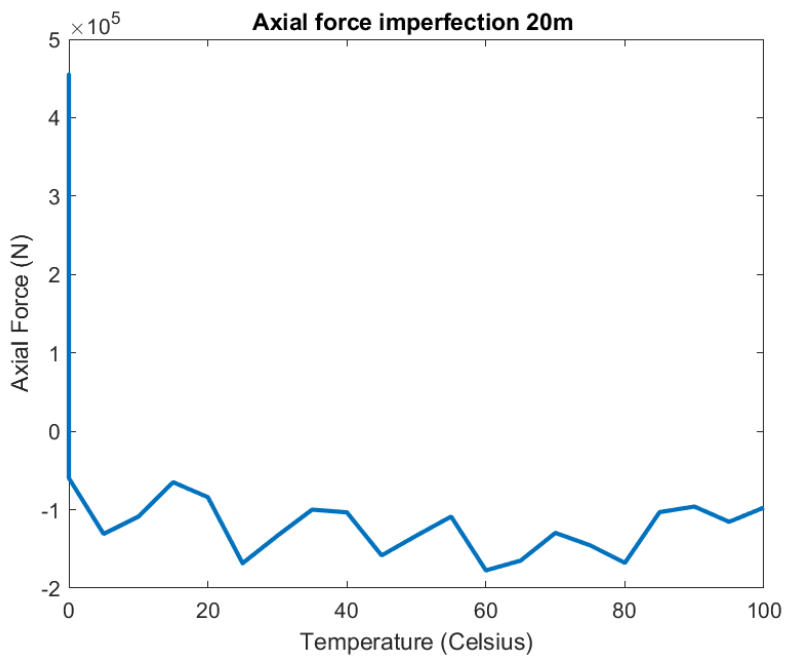


Figure 21: Axial force case 112

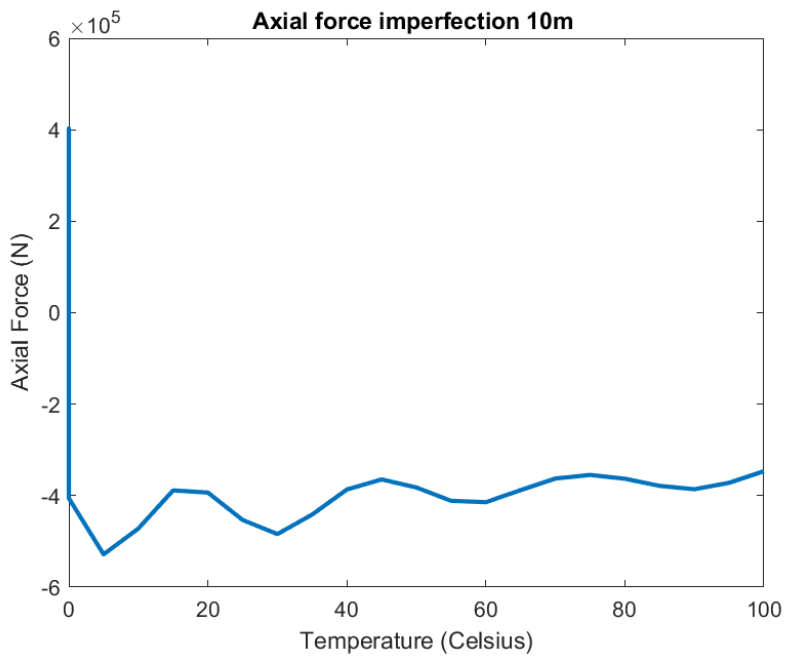


Figure 22: Axial force case 113

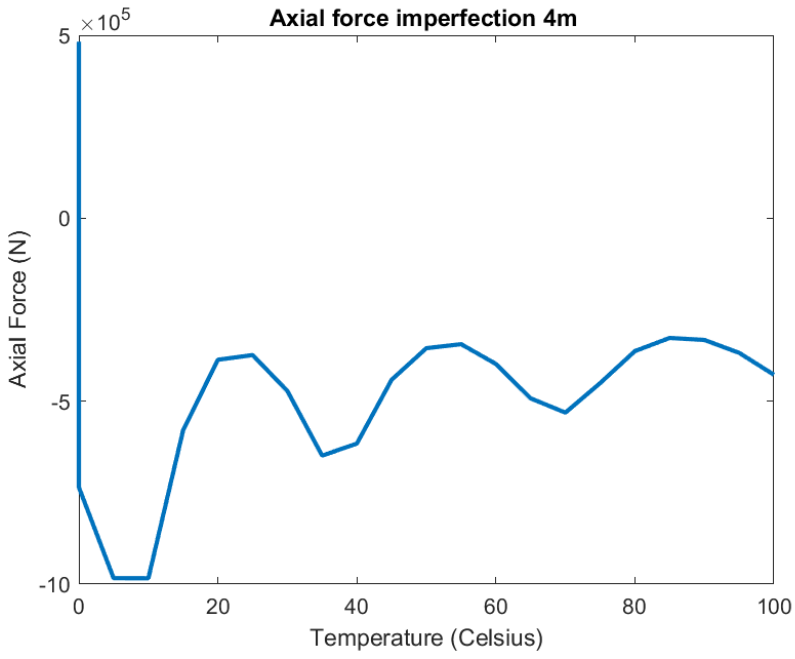


Figure 23: Axial force case 114

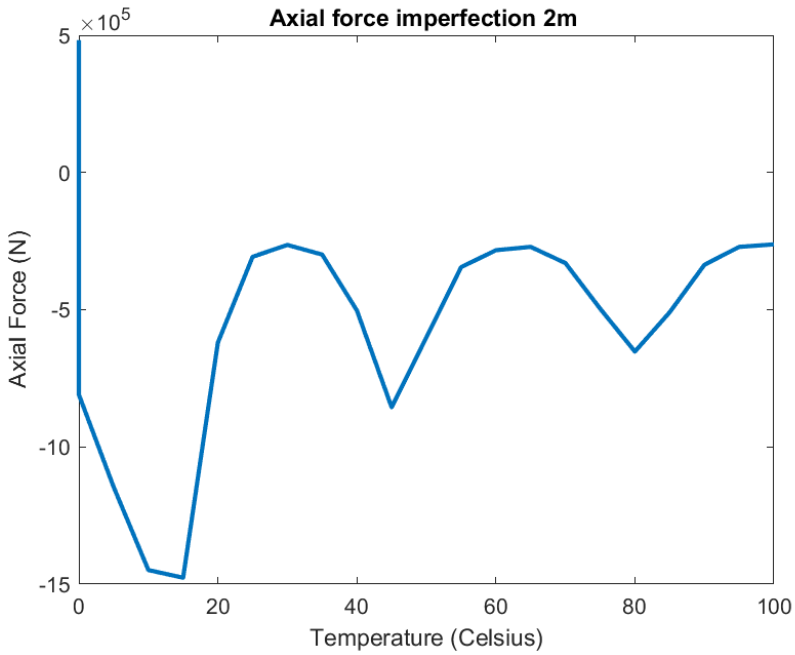


Figure 24: Axial force case 115

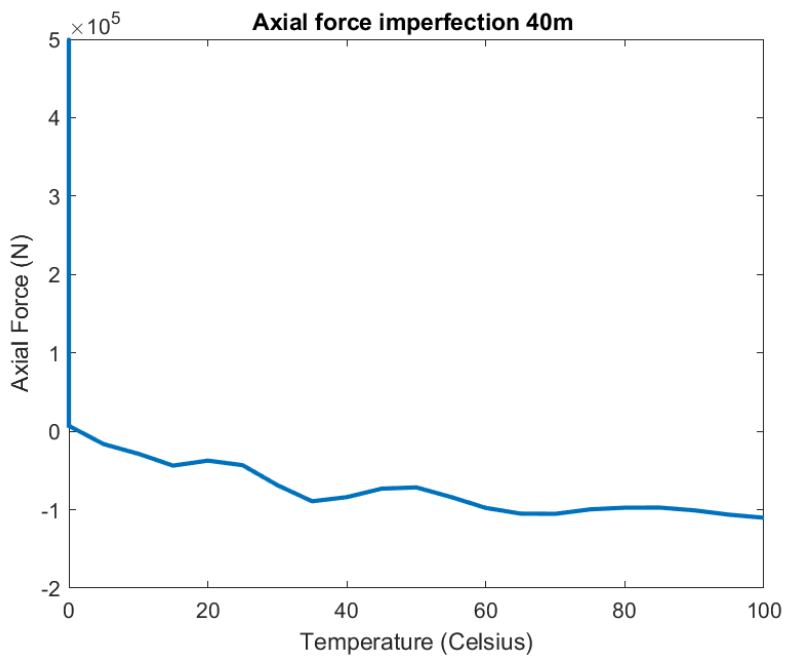


Figure 25: Axial force case 116

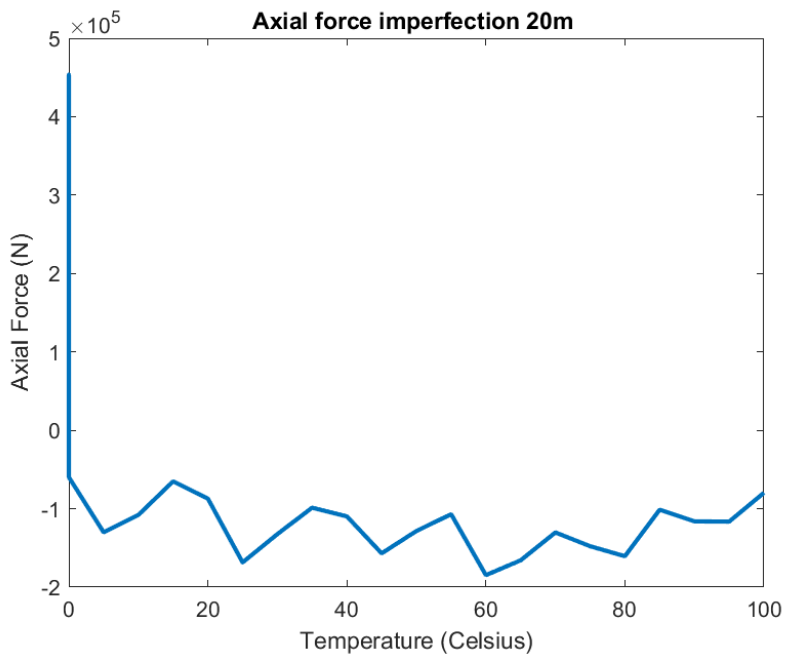


Figure 26: Axial force case 117

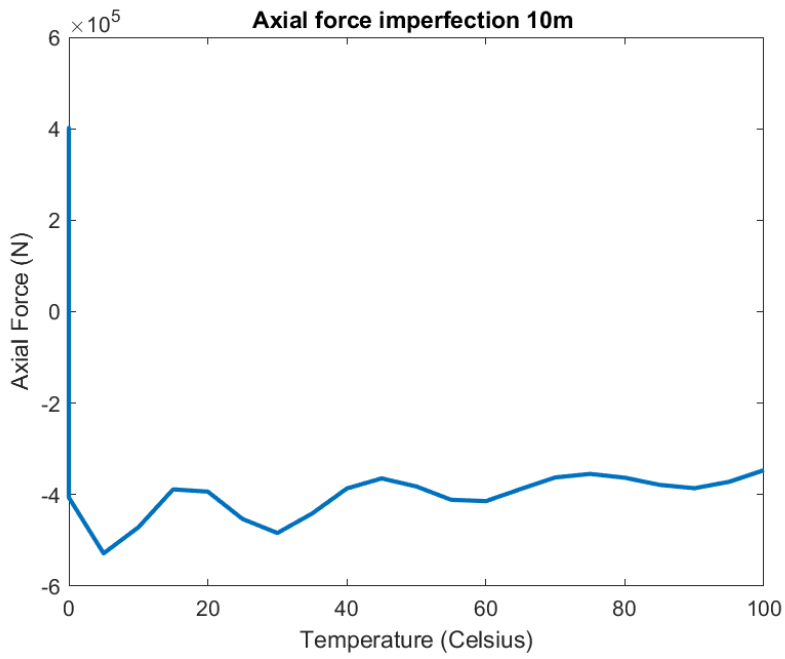


Figure 27: Axial force case 118

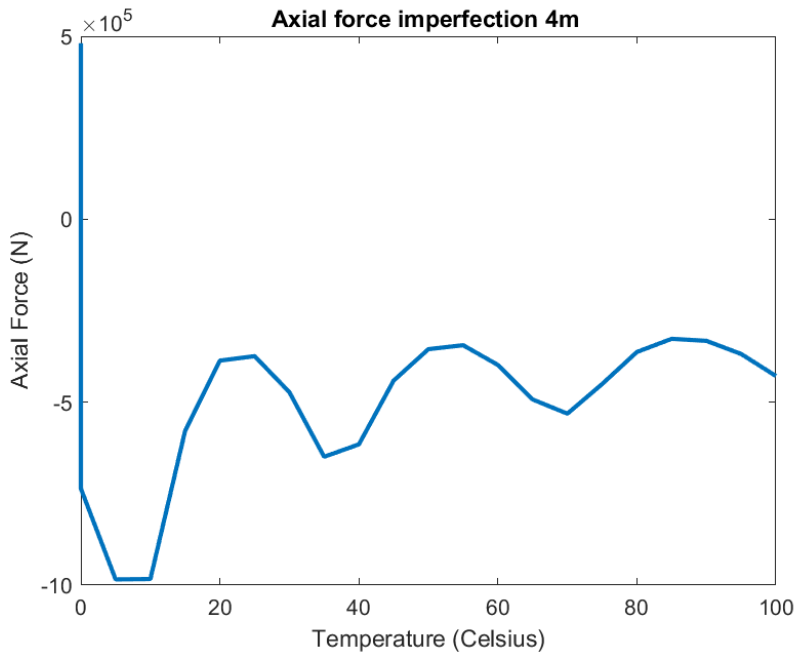


Figure 28: Axial force case 119

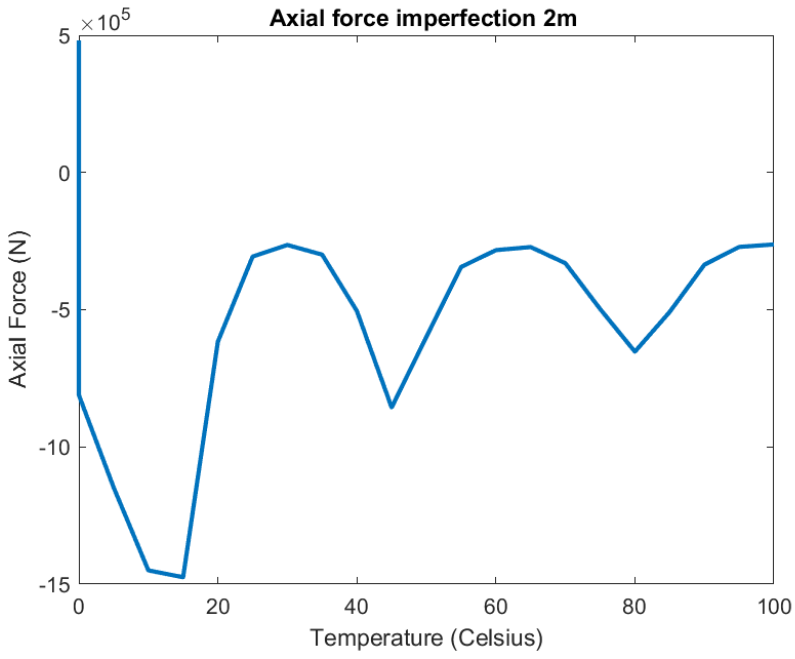


Figure 29: Axial force case 120

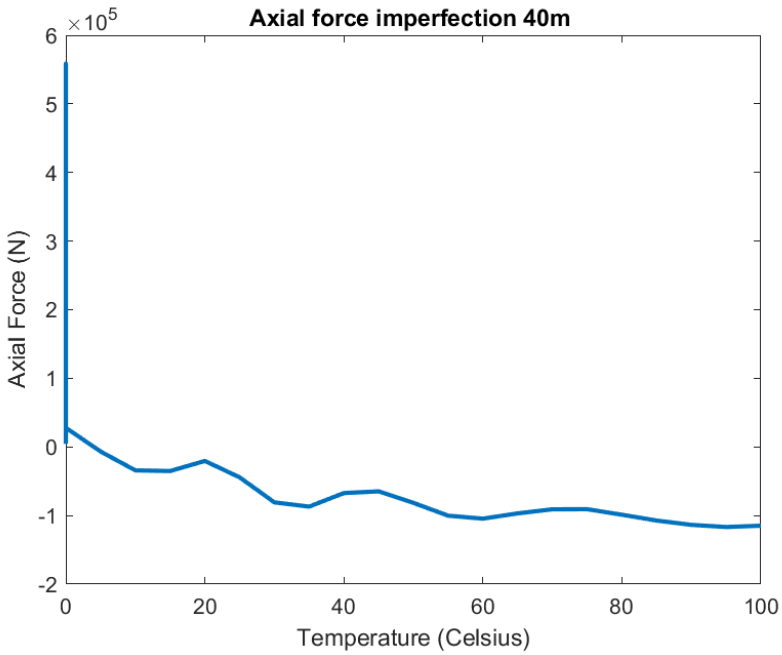


Figure 30: Axial force case 136

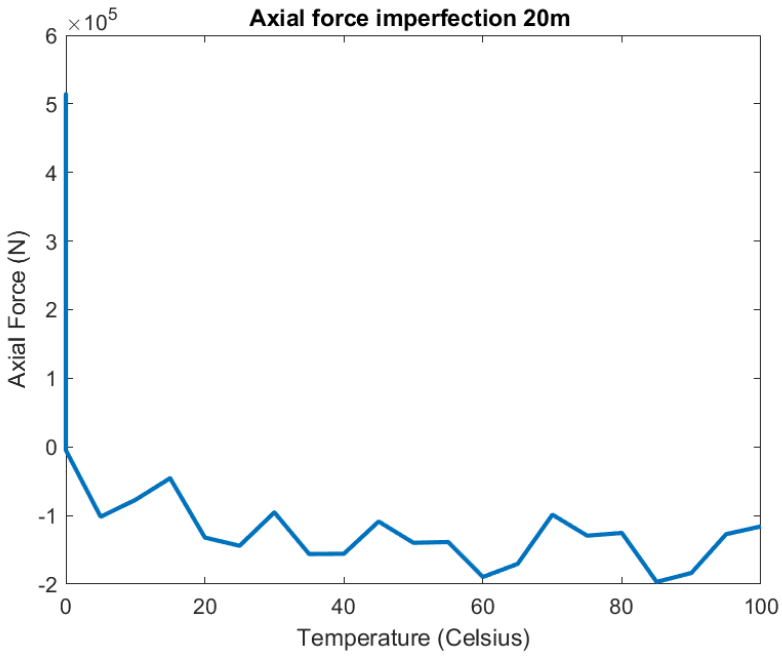


Figure 31: Axial force case 137

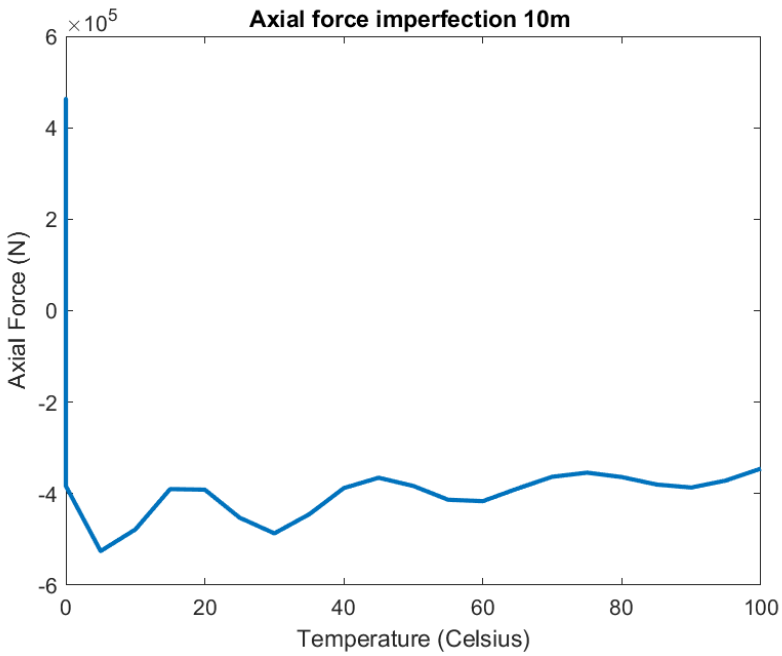


Figure 32: Axial force case 138

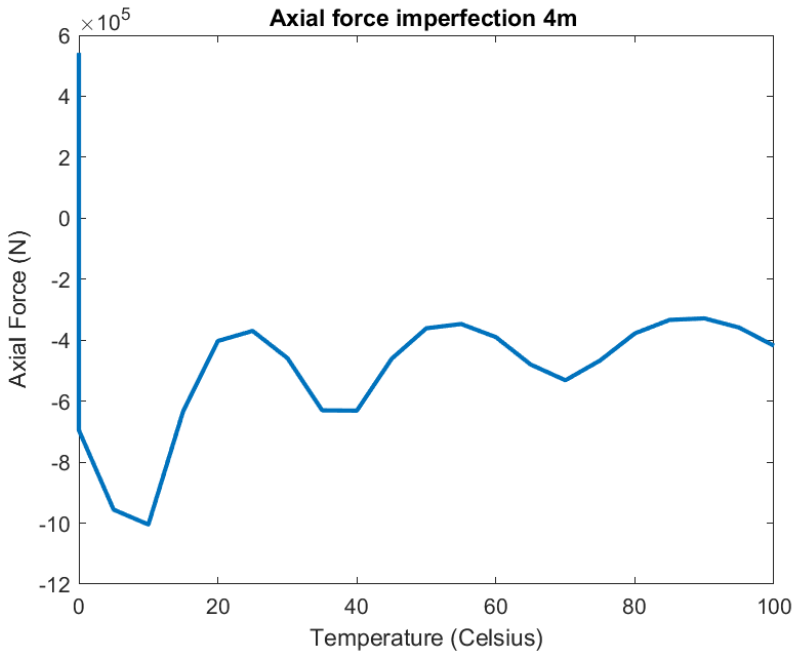


Figure 33: Axial force case 139

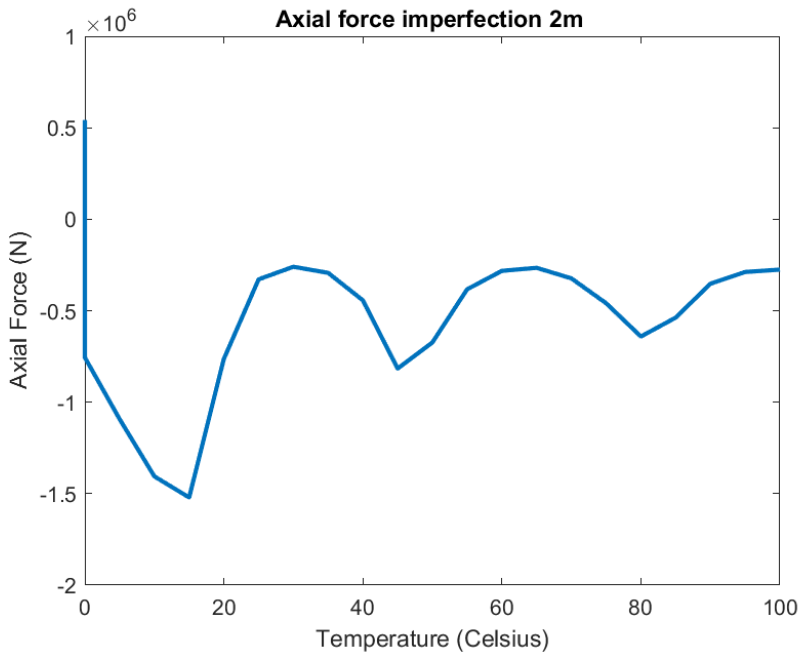


Figure 34: Axial force case 140

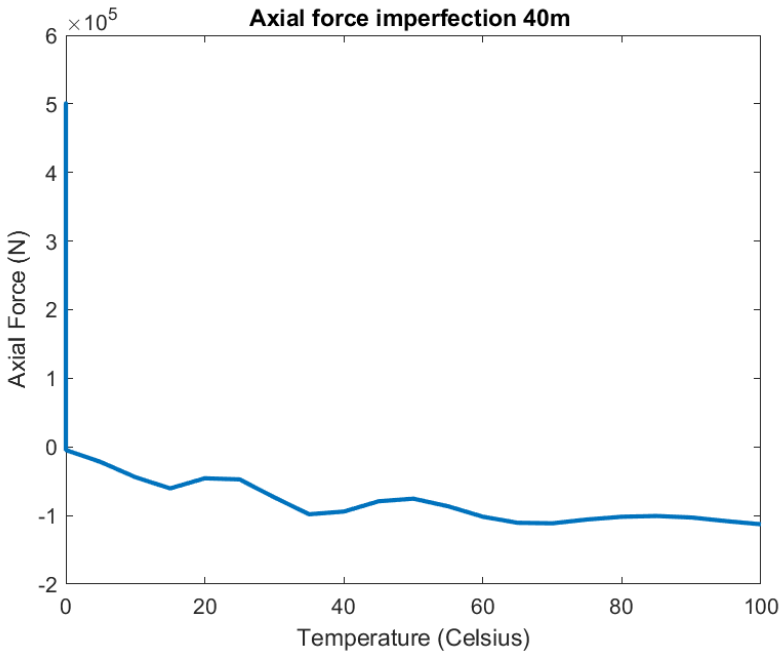


Figure 35: Axial force case 141

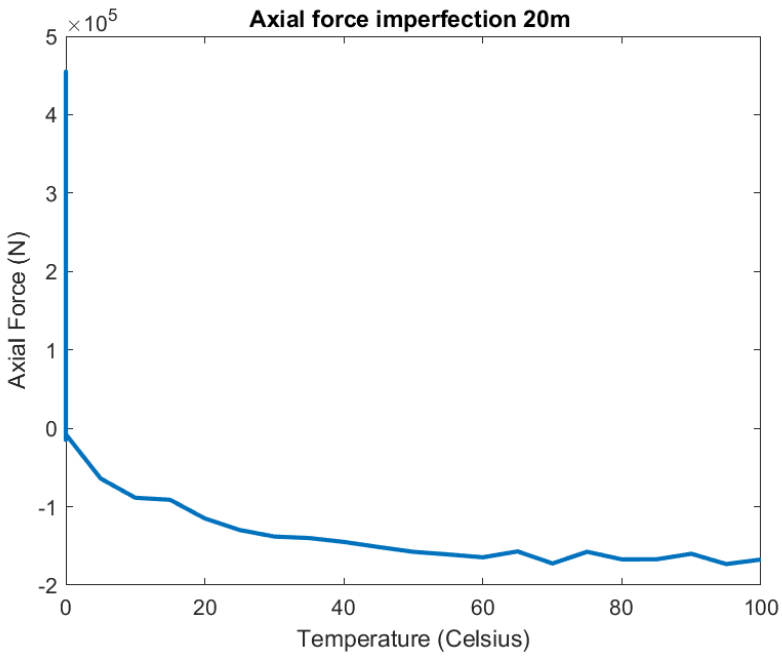


Figure 36: Axial force case 142

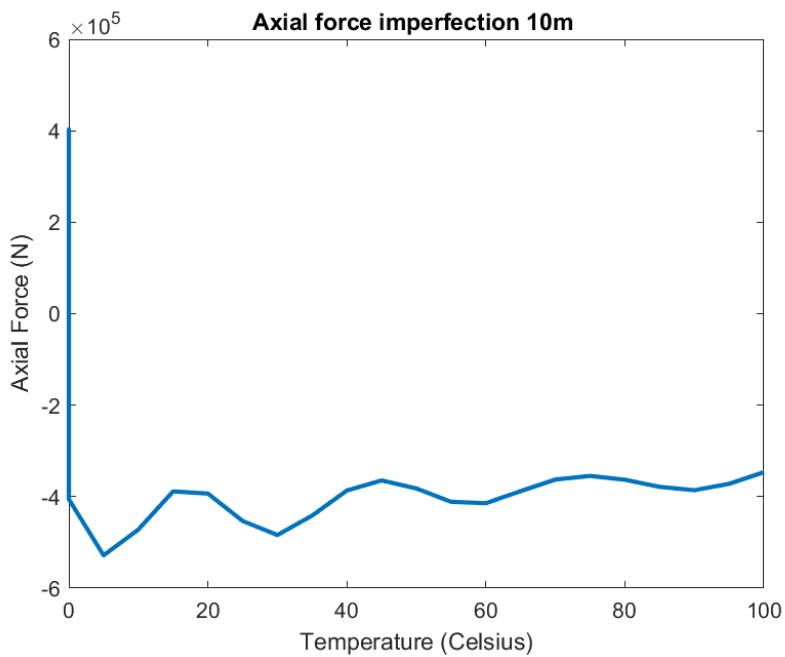


Figure 37: Axial force case 143

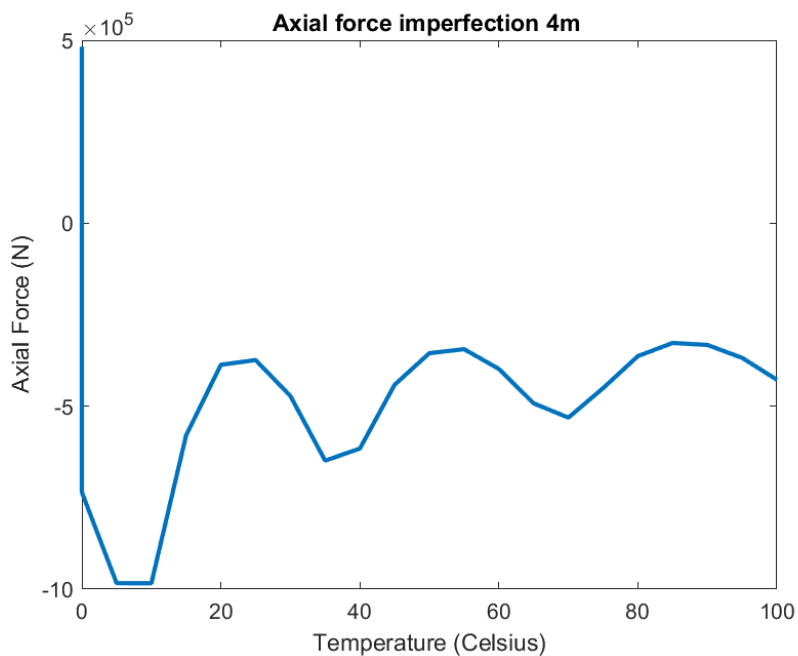


Figure 38: Axial force case 144

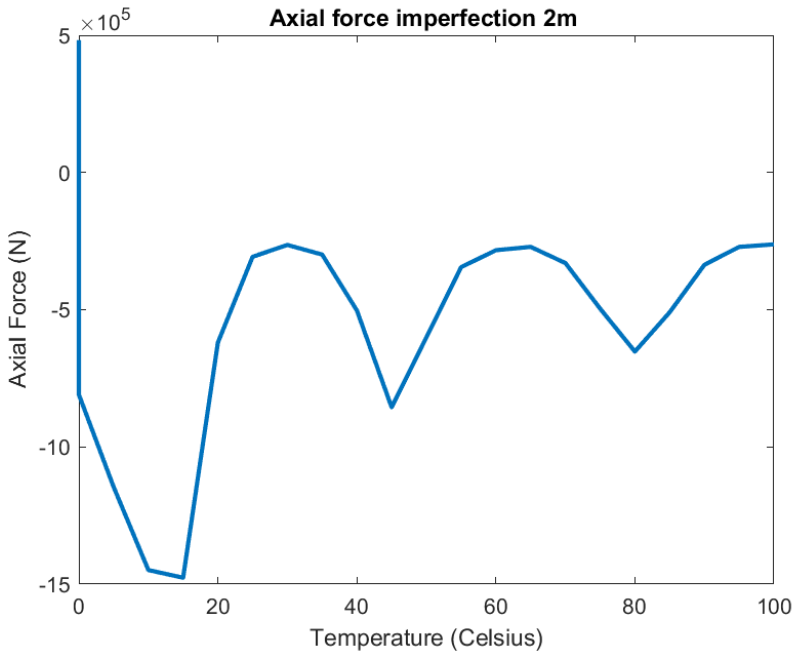


Figure 39: Axial force case 145

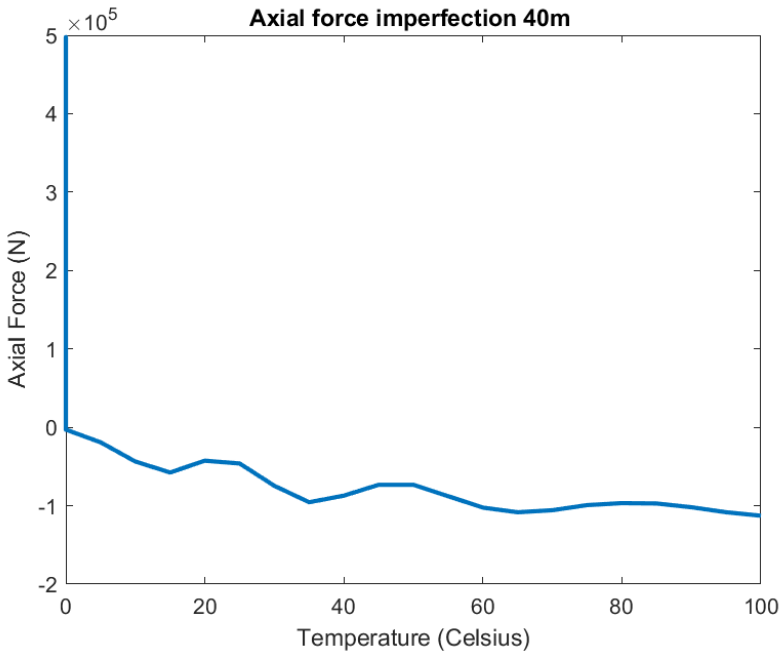


Figure 40: Axial force case 146

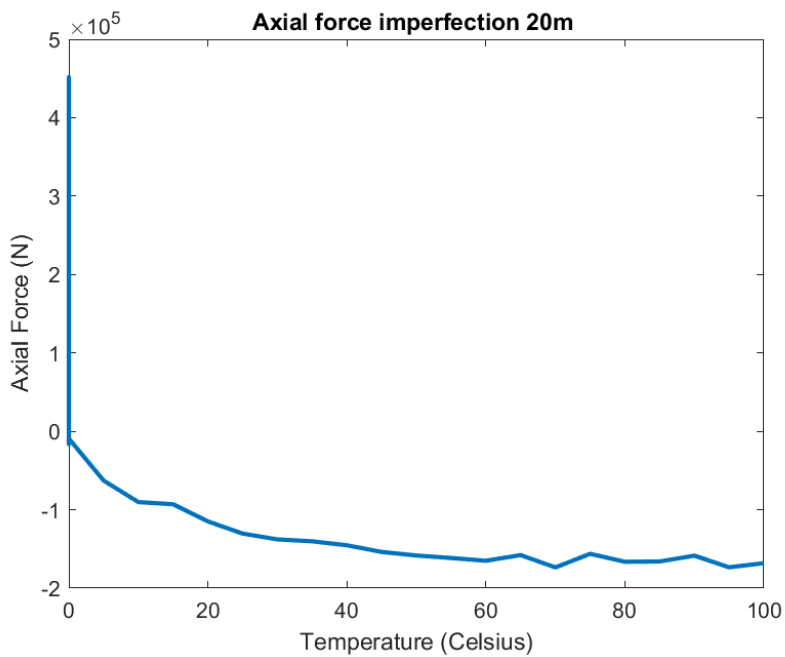


Figure 41: Axial force case 147

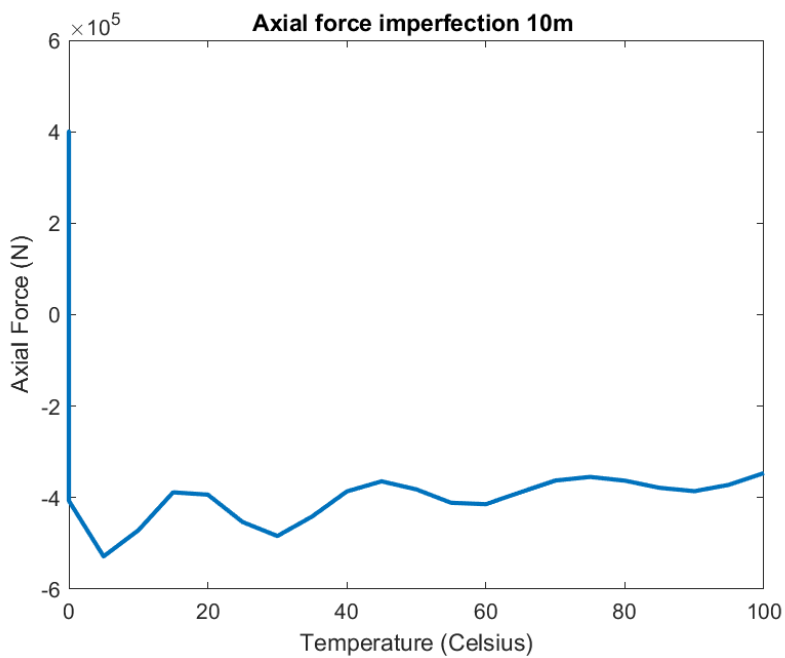


Figure 42: Axial force case 148

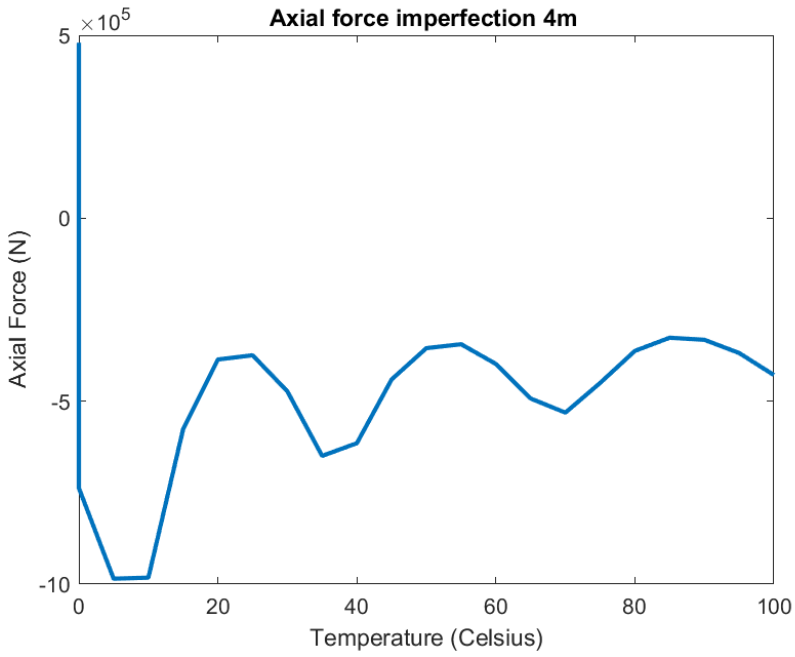


Figure 43: Axial force case 149

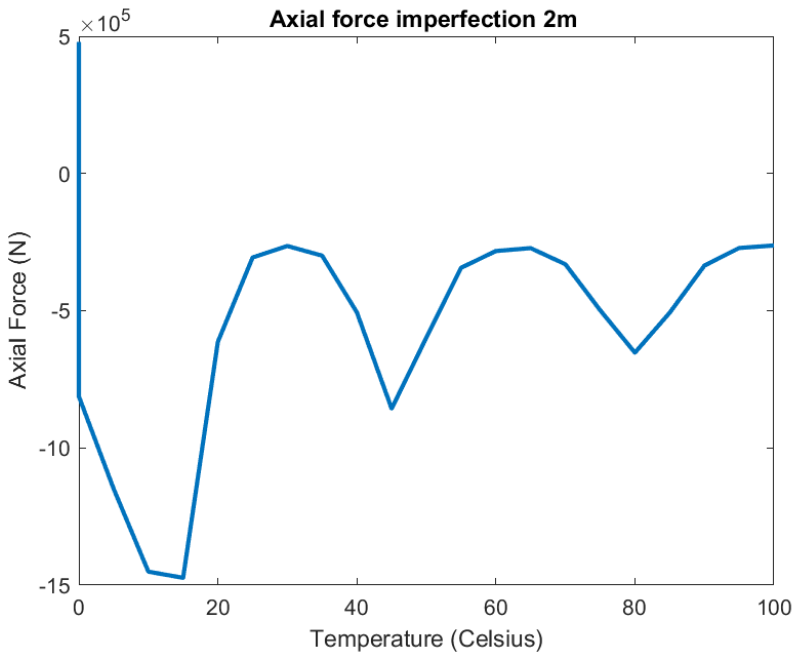


Figure 44: Axial force case 150

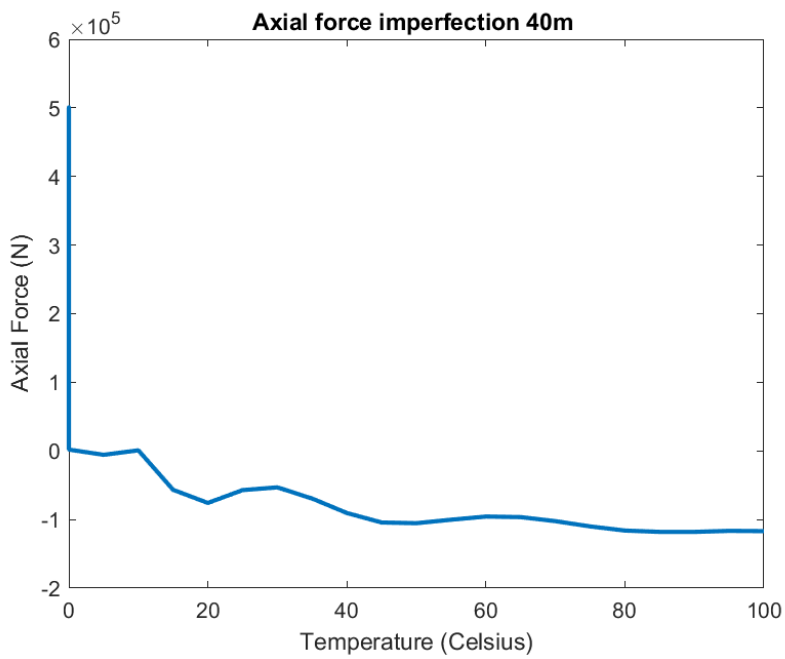


Figure 45: Axial force case 161

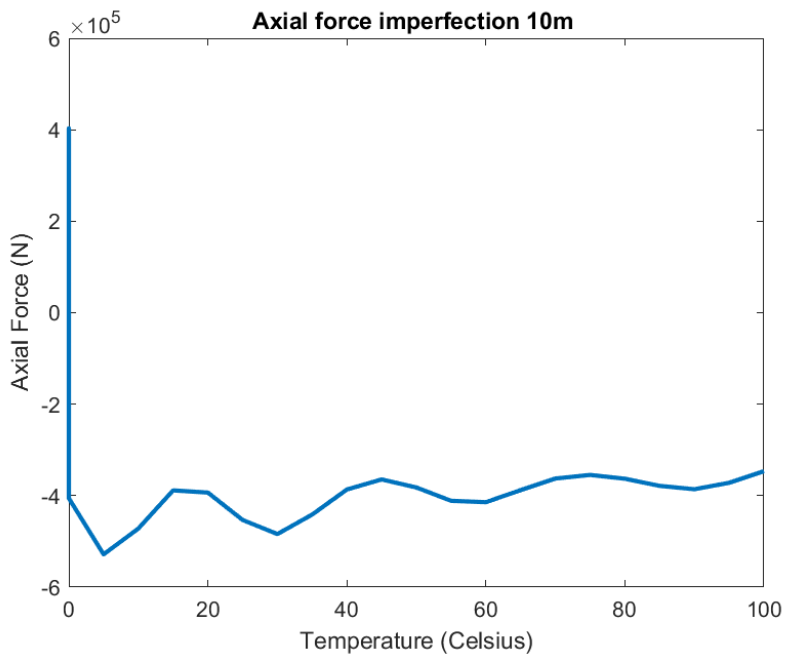


Figure 46: Axial force case 168

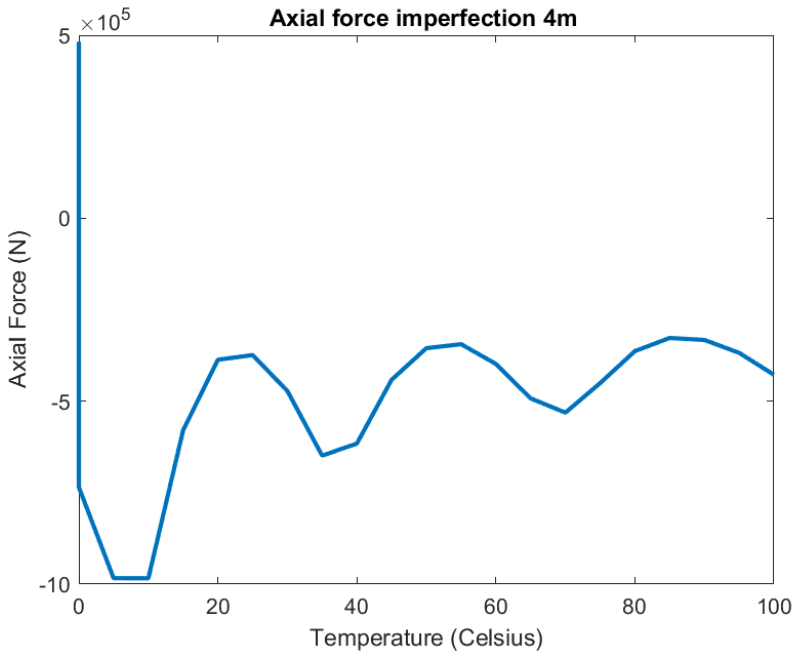


Figure 47: Axial force case 169

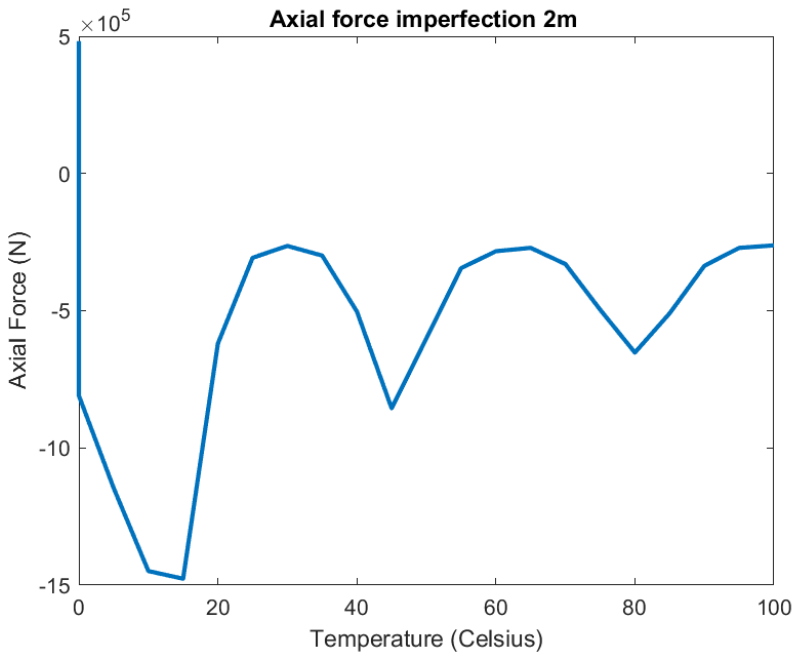


Figure 48: Axial force case 170

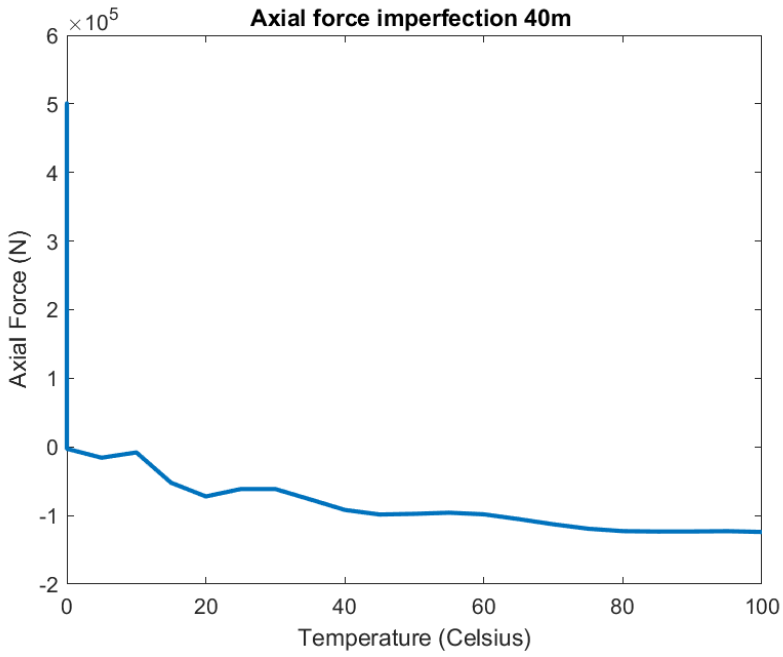


Figure 49: Axial force case 171

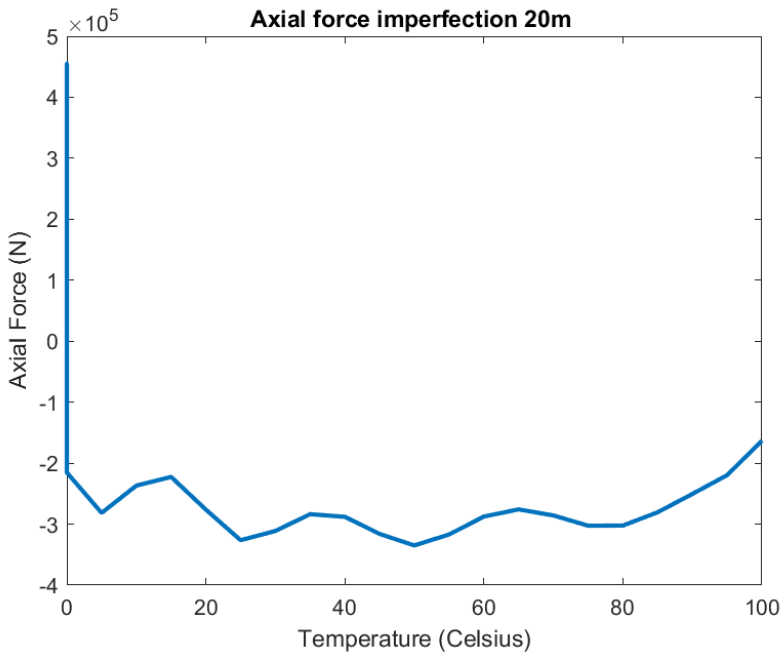


Figure 50: Axial force case 172

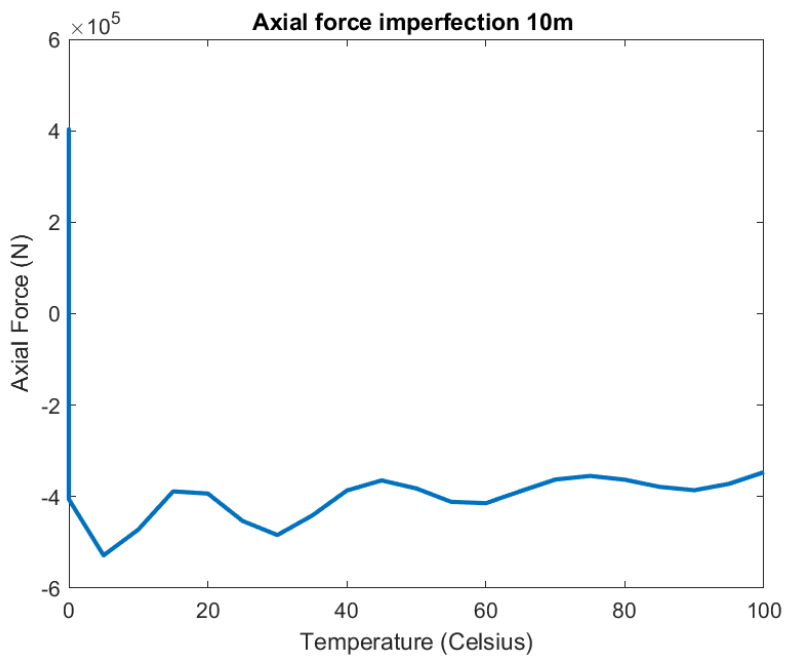


Figure 51: Axial force case 173

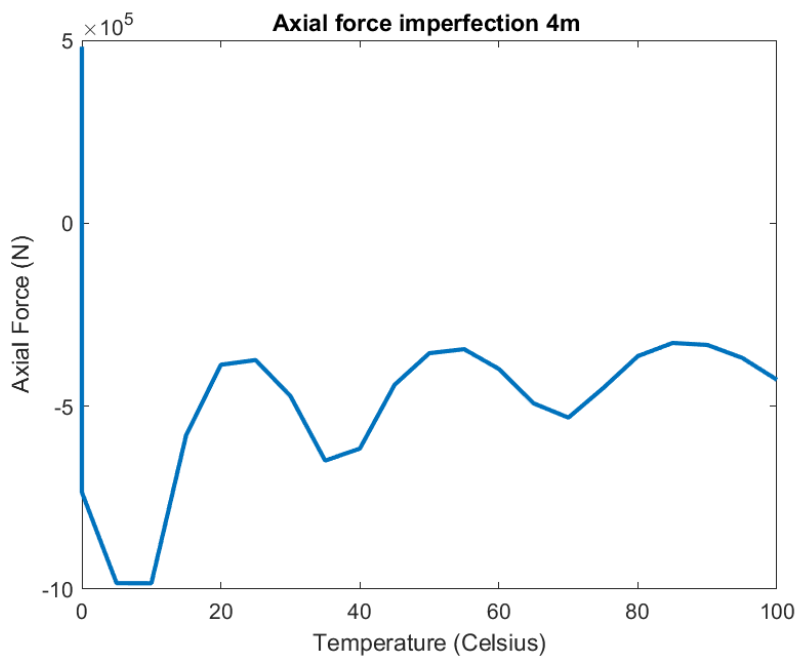


Figure 52: Axial force case 174

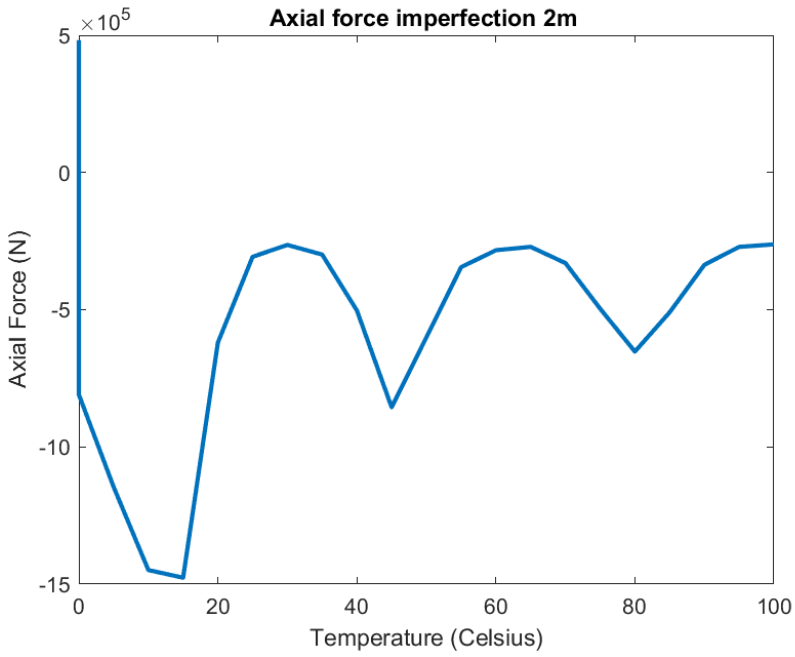


Figure 53: Axial force case 175

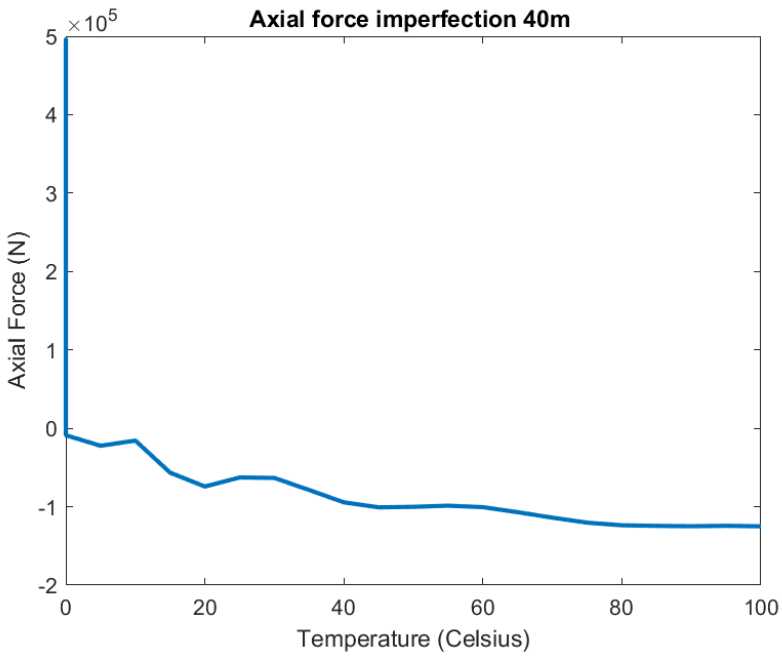


Figure 54: Axial force case 176

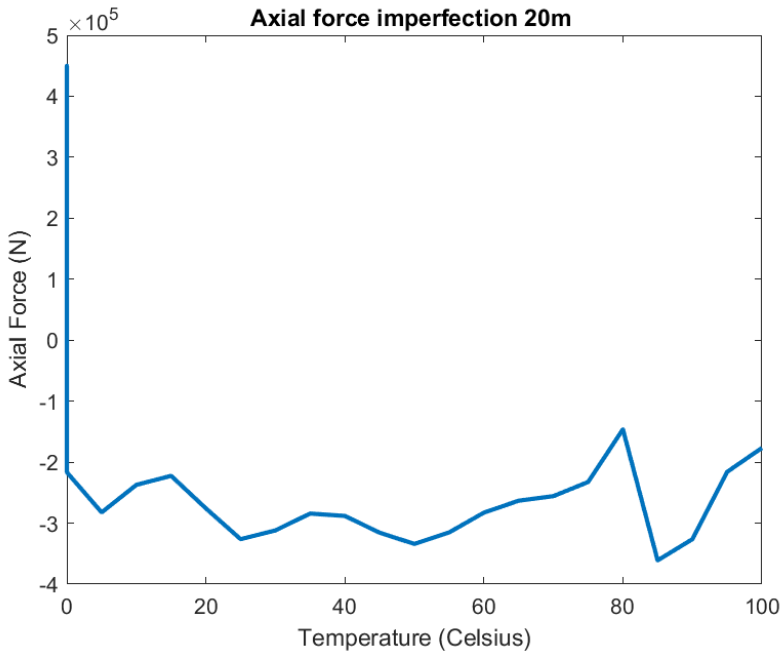


Figure 55: Axial force case 177

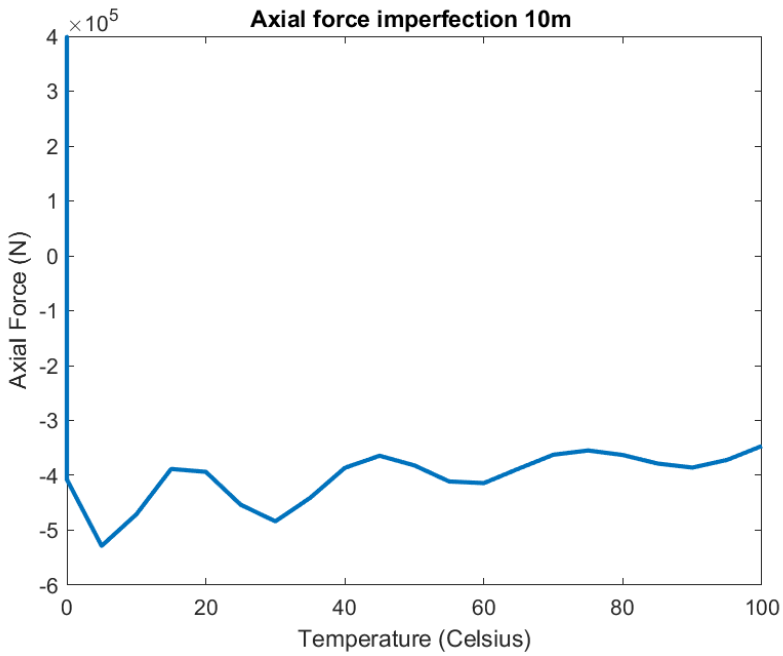


Figure 56: Axial force case 178

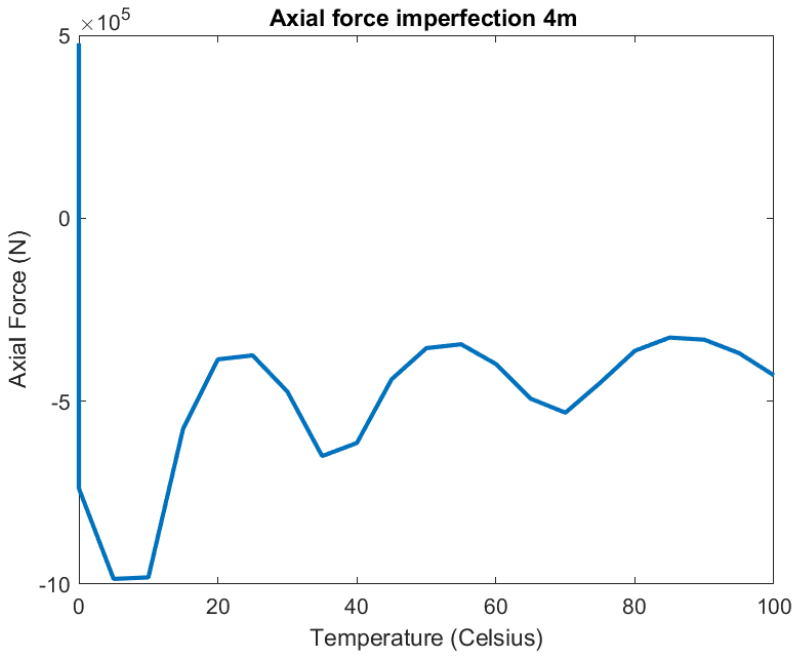


Figure 57: Axial force case 179

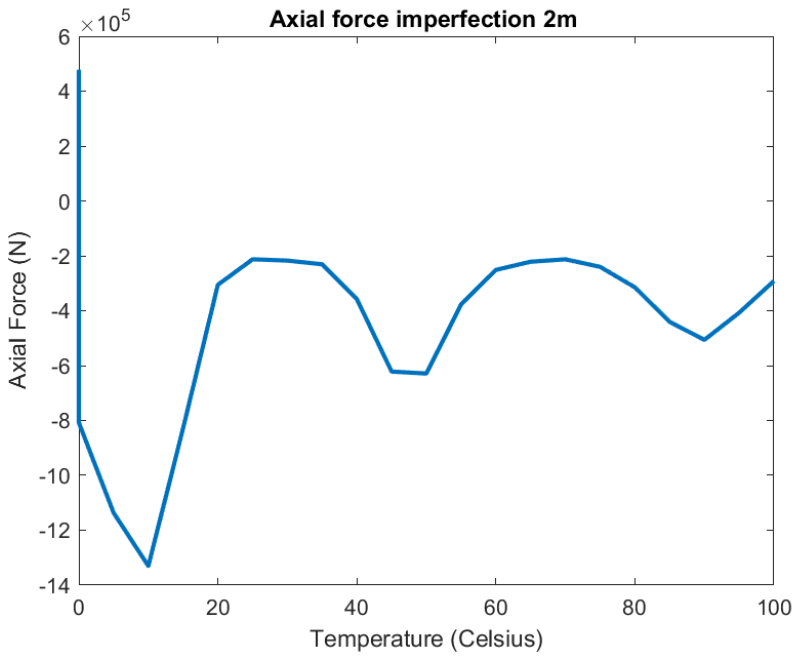


Figure 58: Axial force case 180

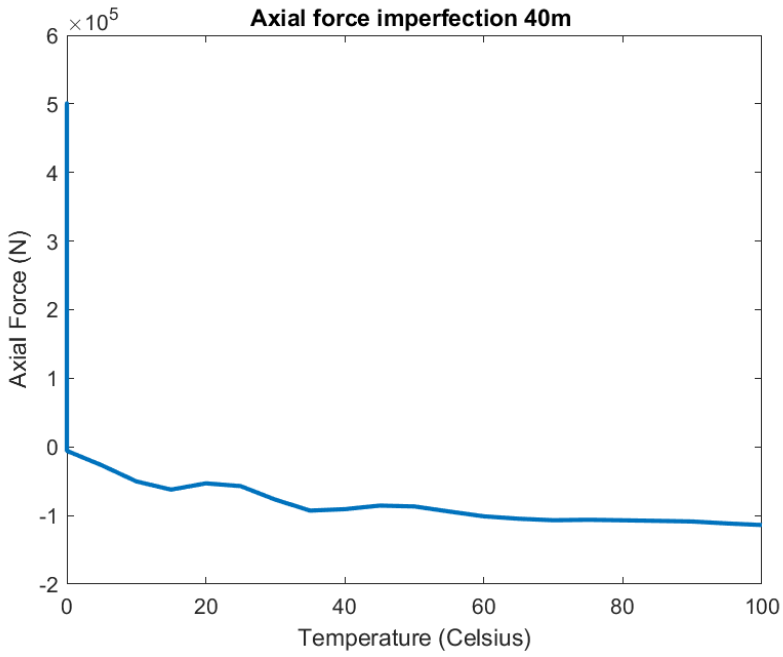


Figure 59: Axial force case 181

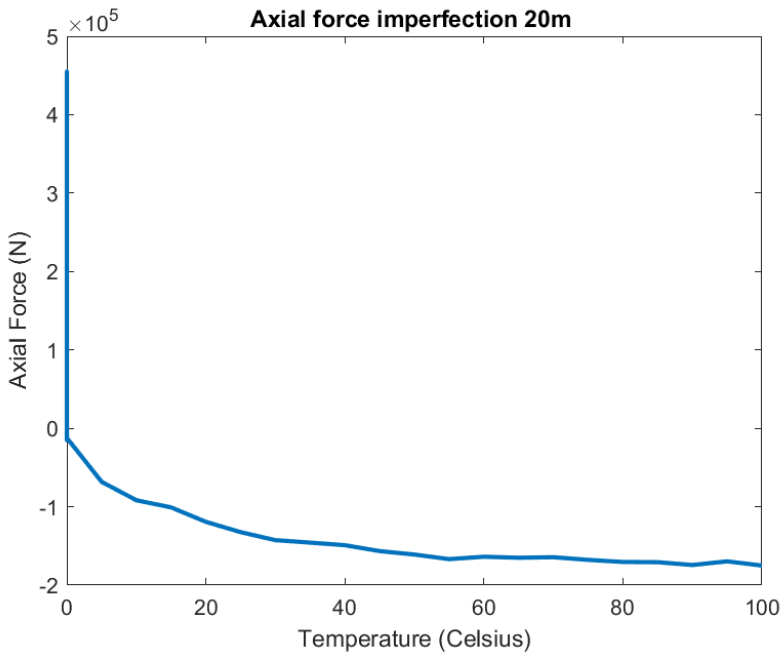


Figure 60: Axial force case 182

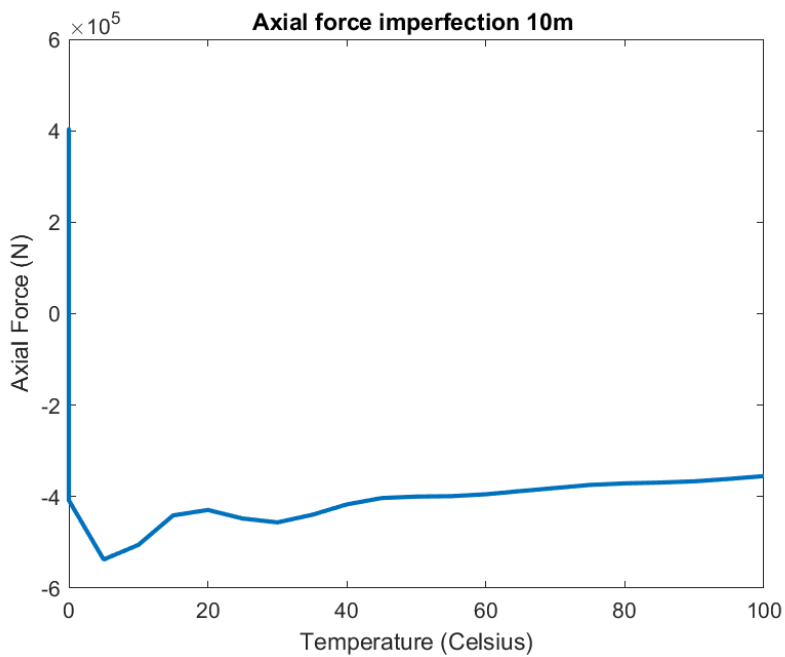


Figure 61: Axial force case 183

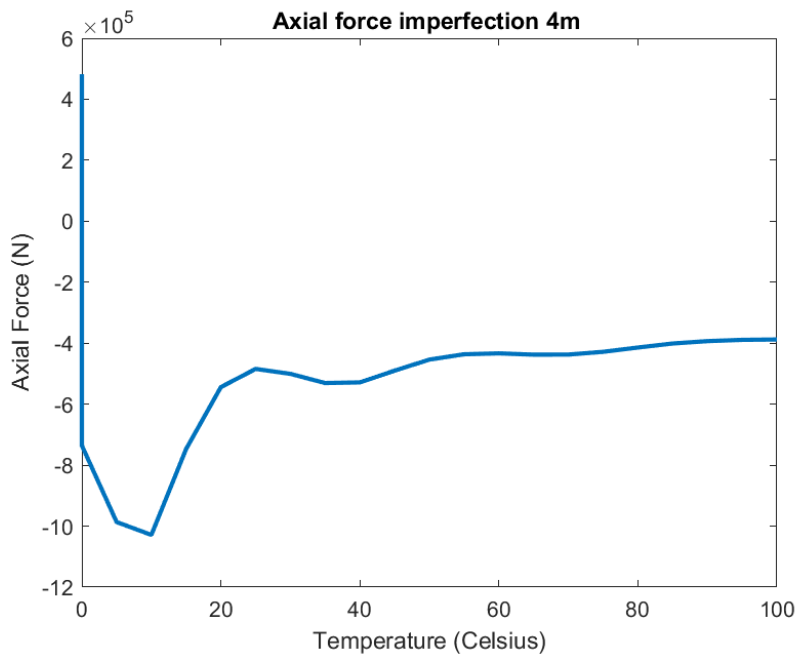


Figure 62: Axial force case 184

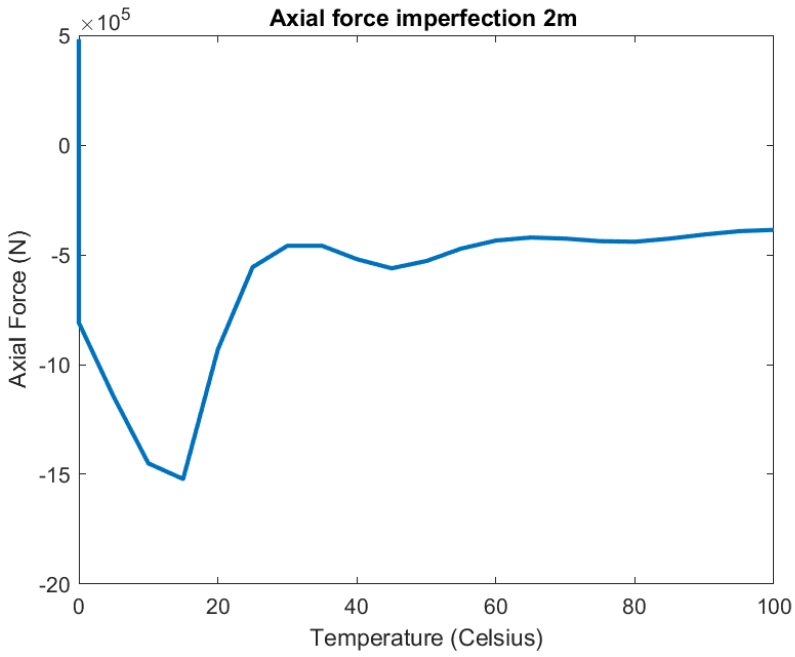


Figure 63: Axial force case 185

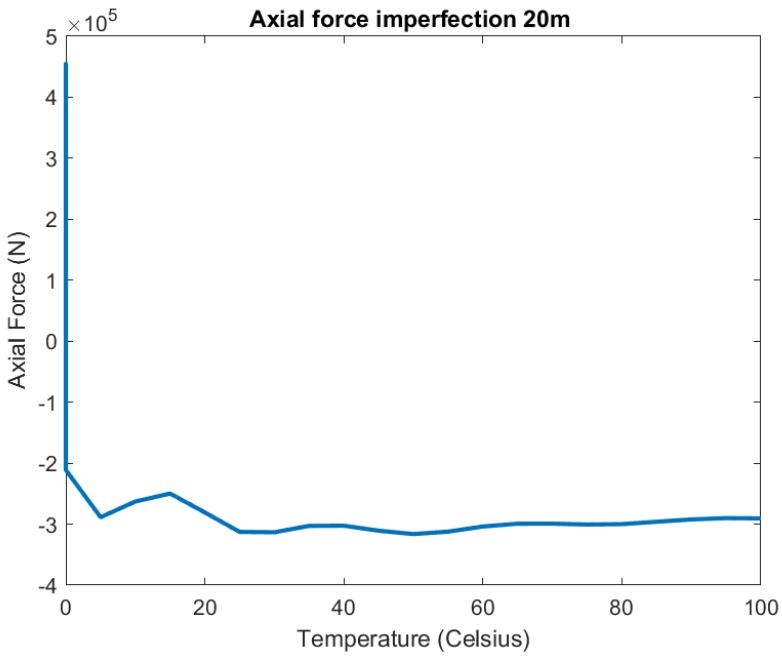


Figure 64: Axial force case 187

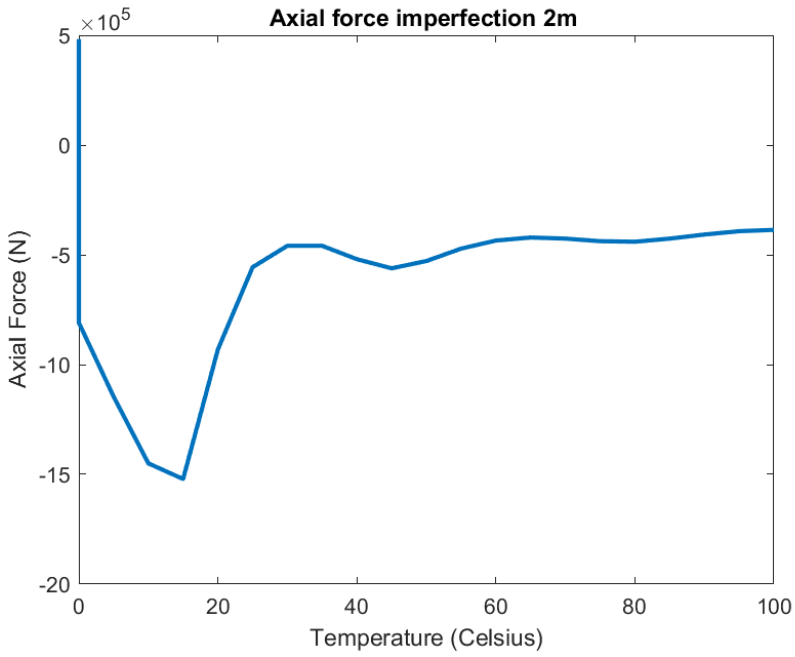


Figure 65: Axial force case 190

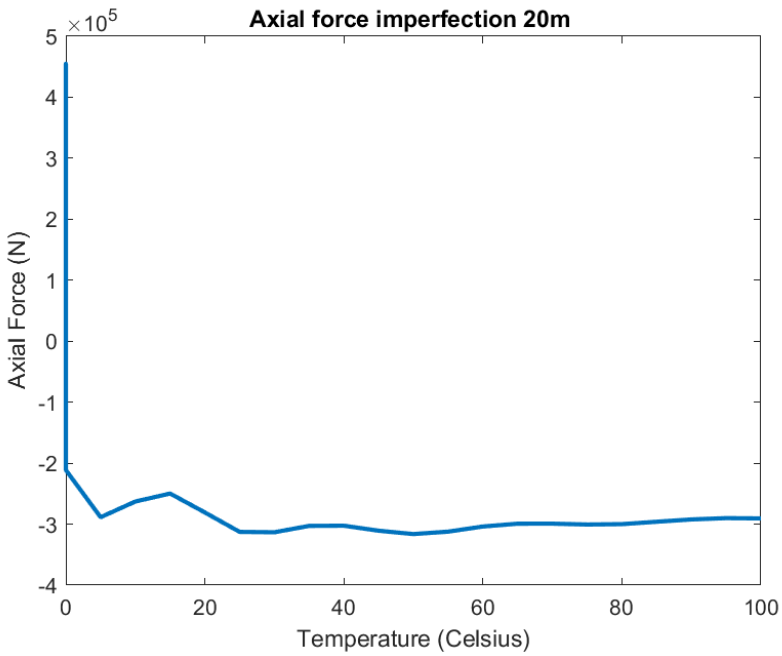


Figure 66: Axial force case 192

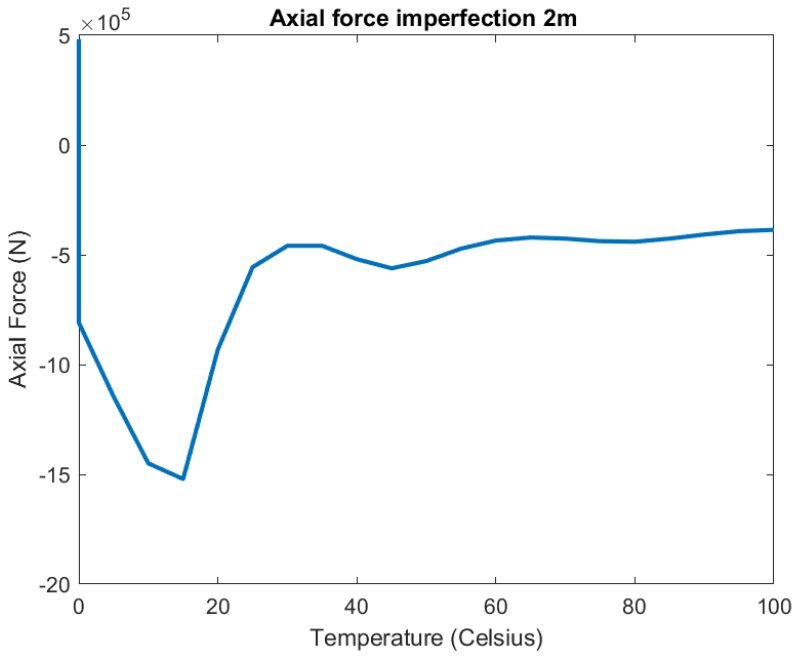


Figure 67: Axial force case 195

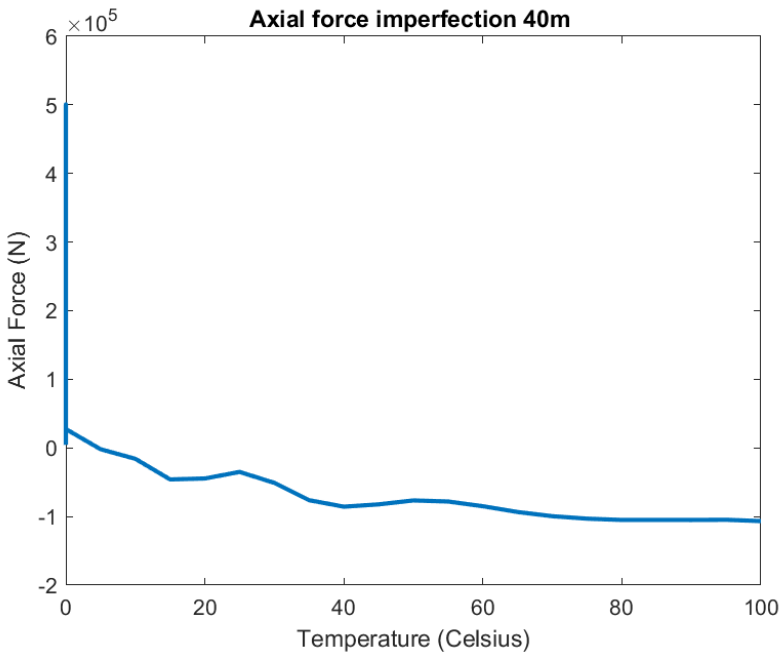


Figure 68: Axial force case 196

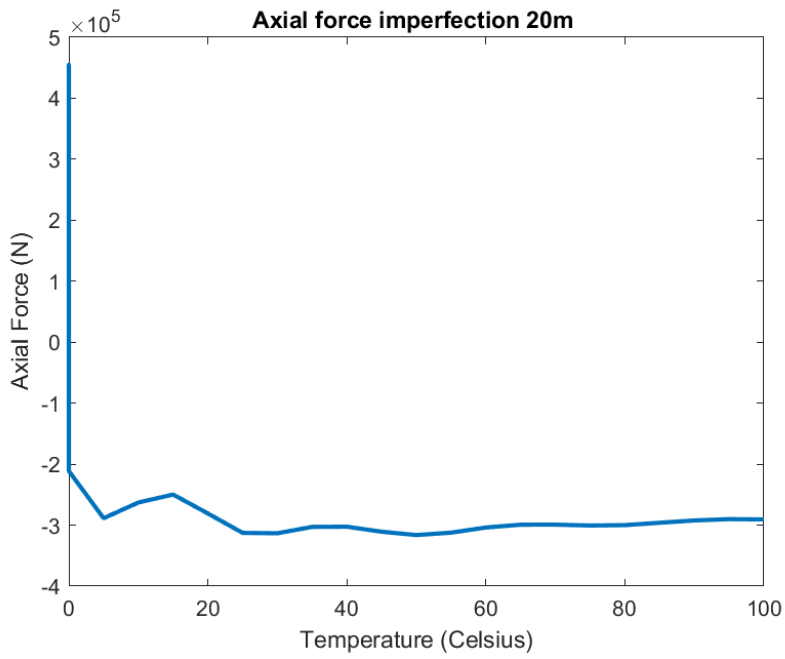


Figure 69: Axial force case 197

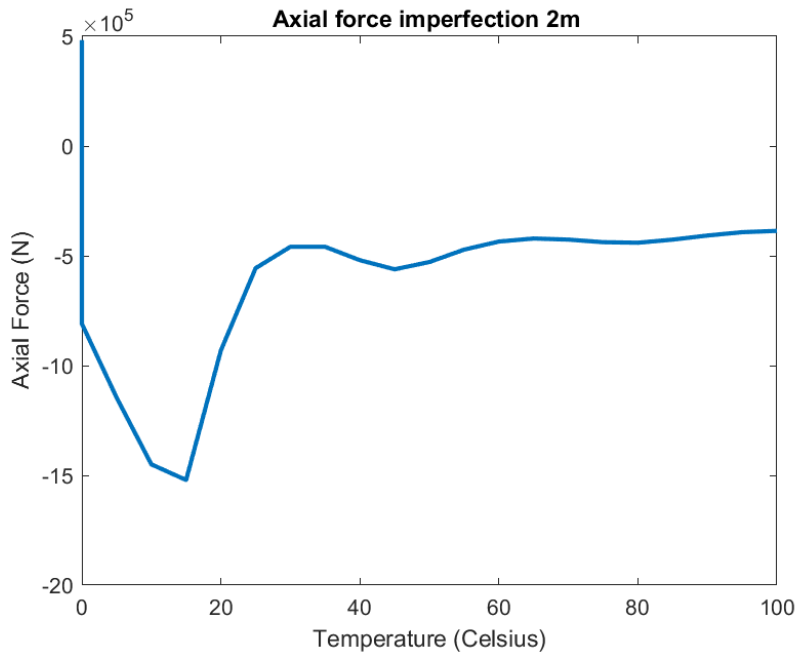


Figure 70: Axial force case 200

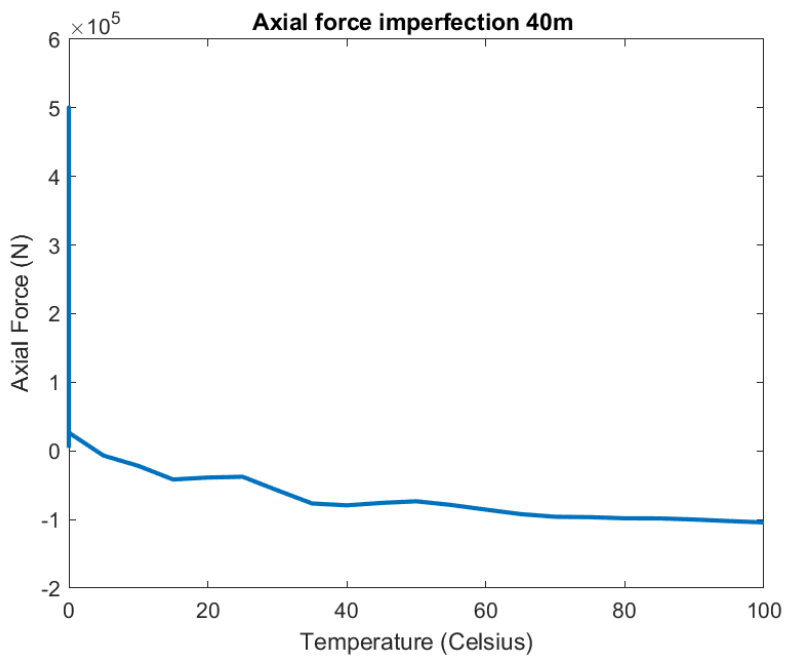


Figure 71: Axial force case 201

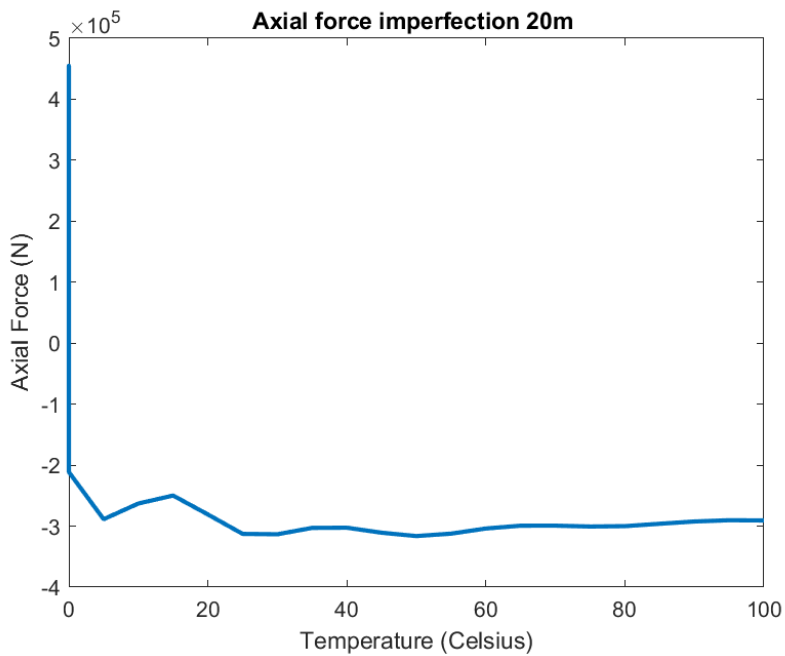


Figure 72: Axial force case 202

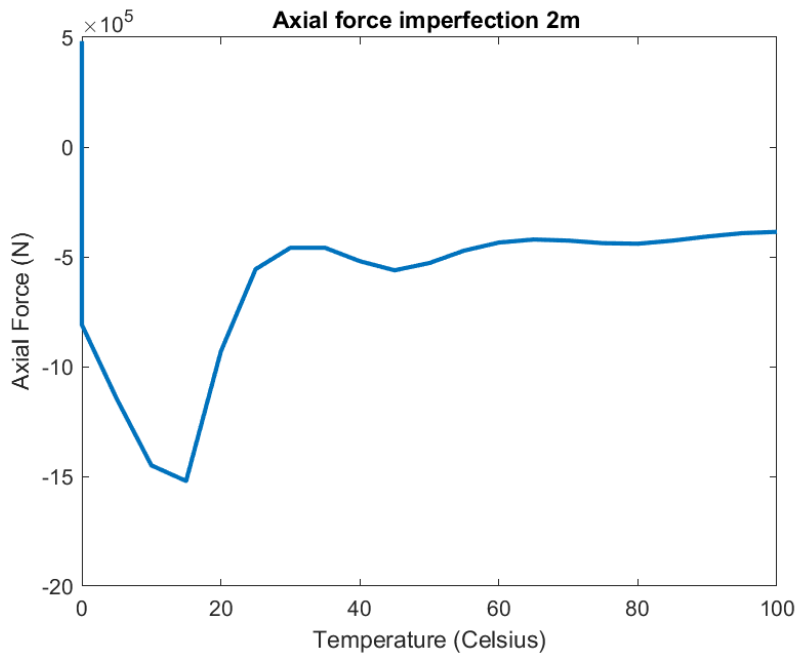


Figure 73: Axial force case 205

C.2 Rotation of pipeline

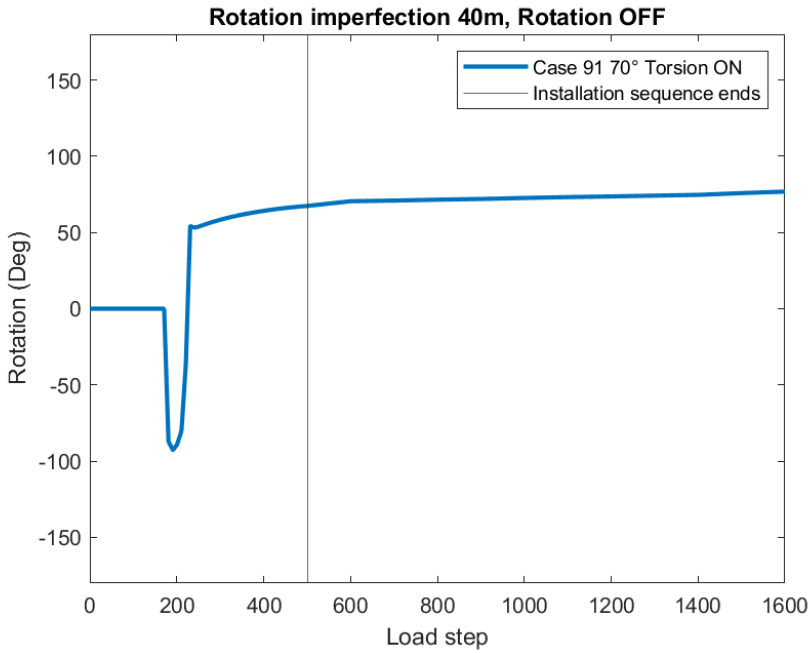


Figure 74: Rotation Case 91

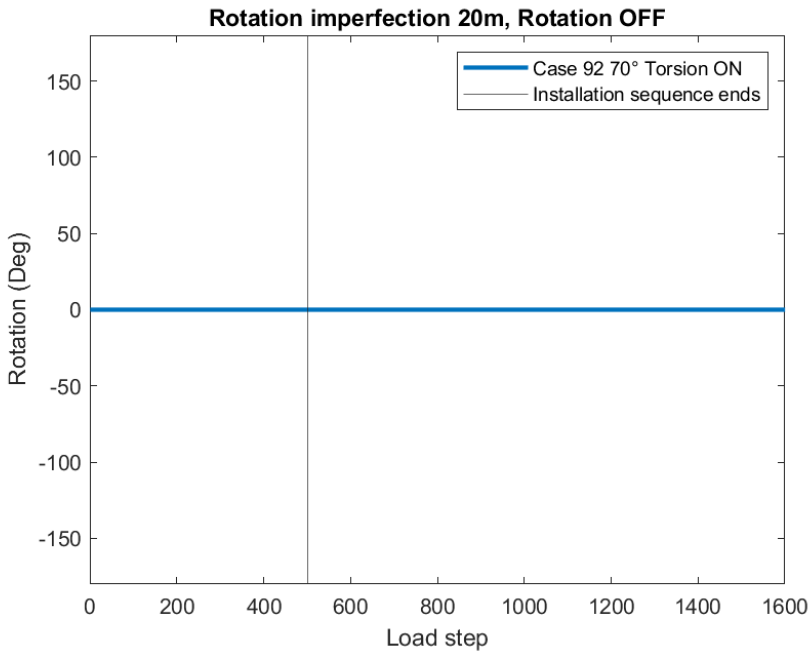


Figure 75: Rotation Case 92

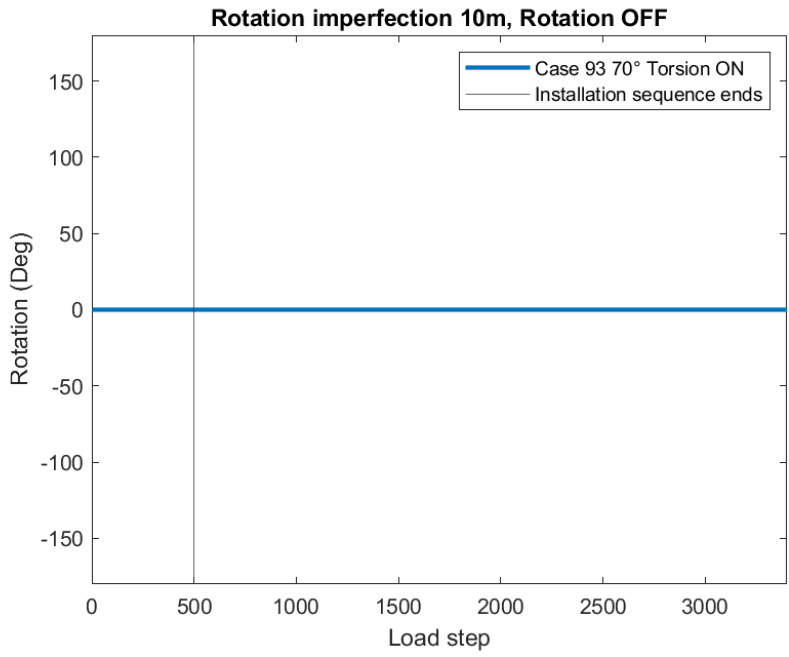


Figure 76: Rotation Case 93

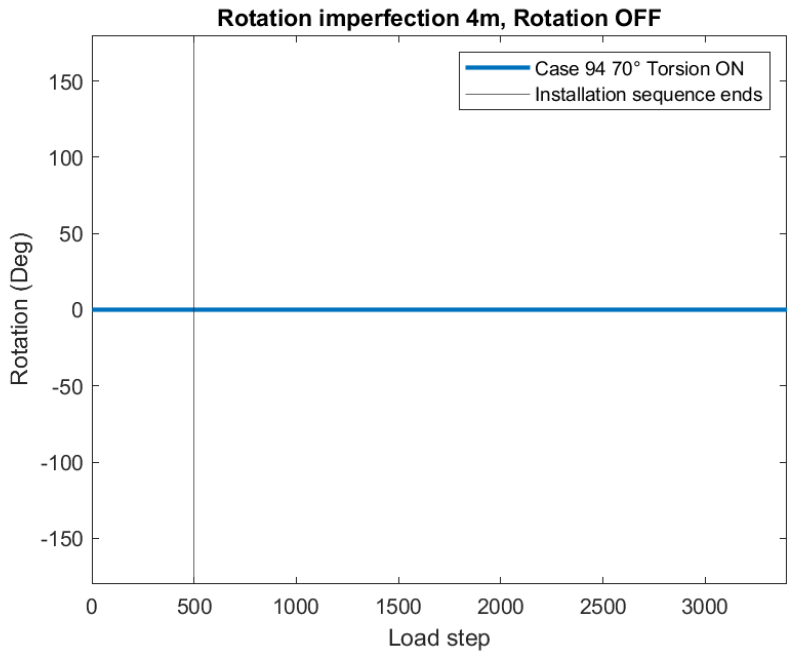


Figure 77: Rotation Case 94

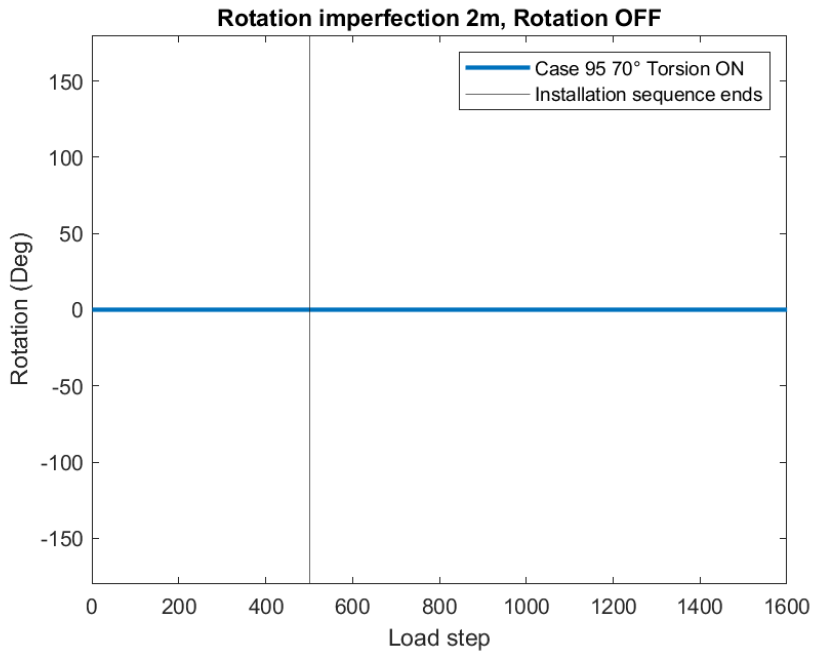


Figure 78: Rotation Case 95

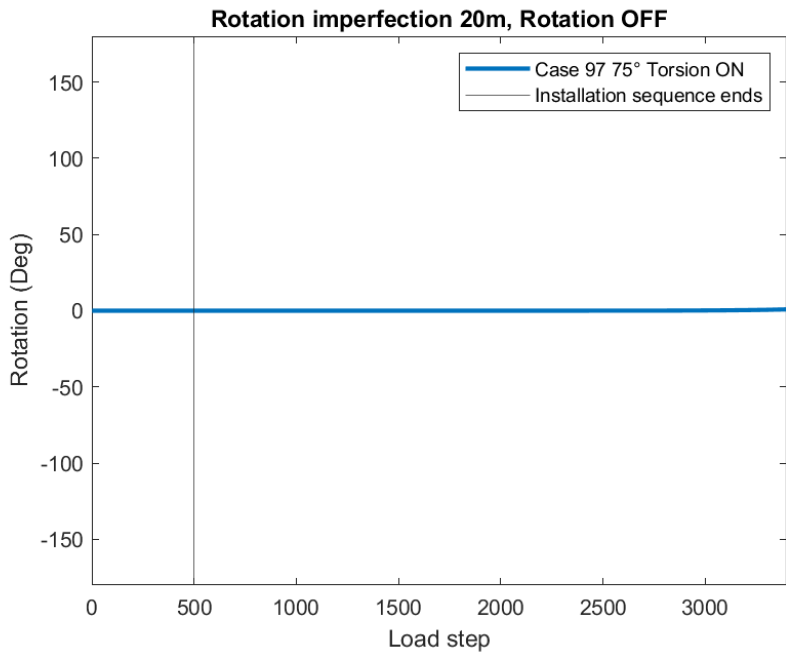


Figure 79: Rotation Case 97

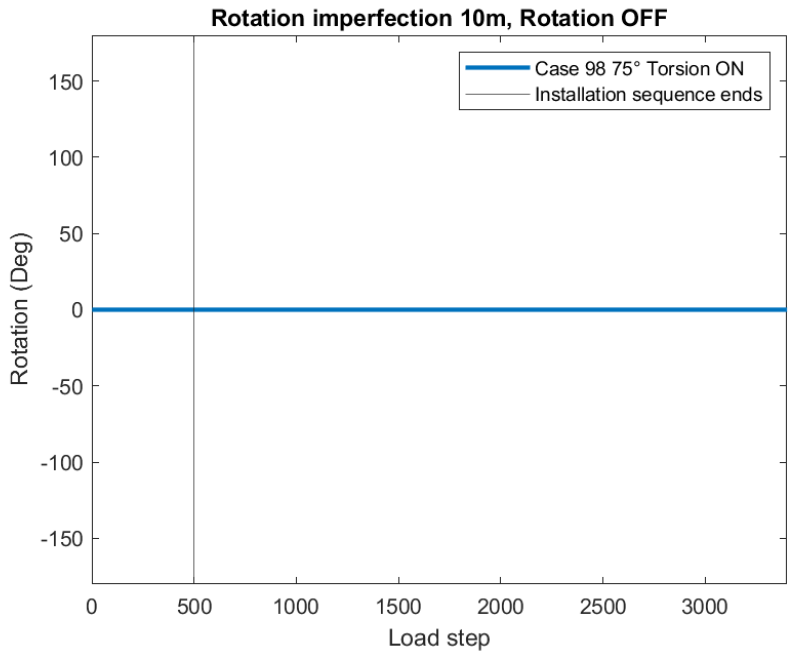


Figure 80: Rotation Case 98

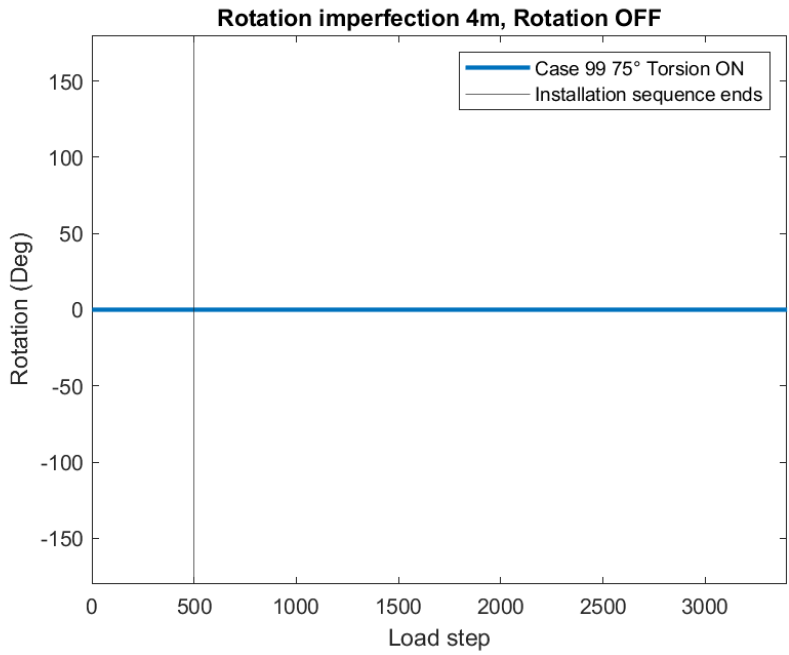


Figure 81: Rotation Case 99

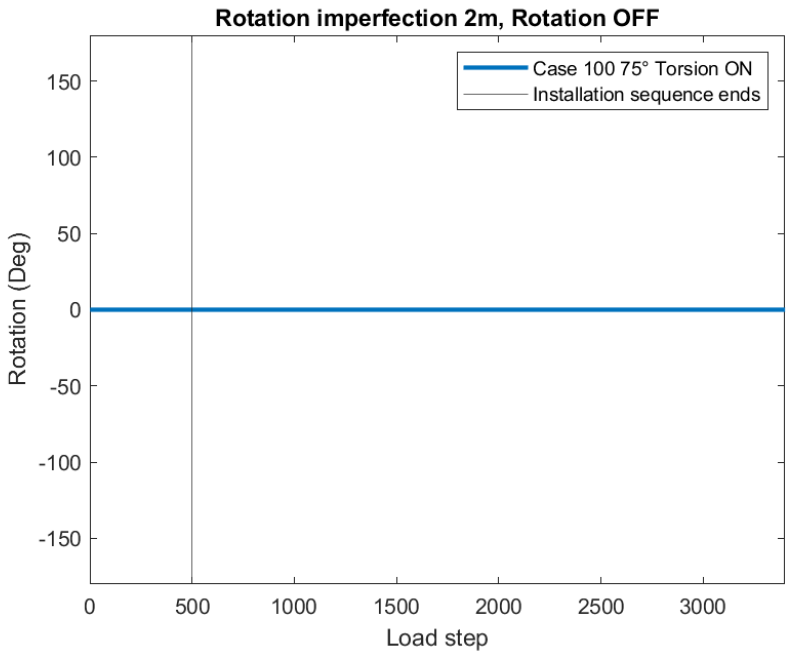


Figure 82: Rotation Case 100

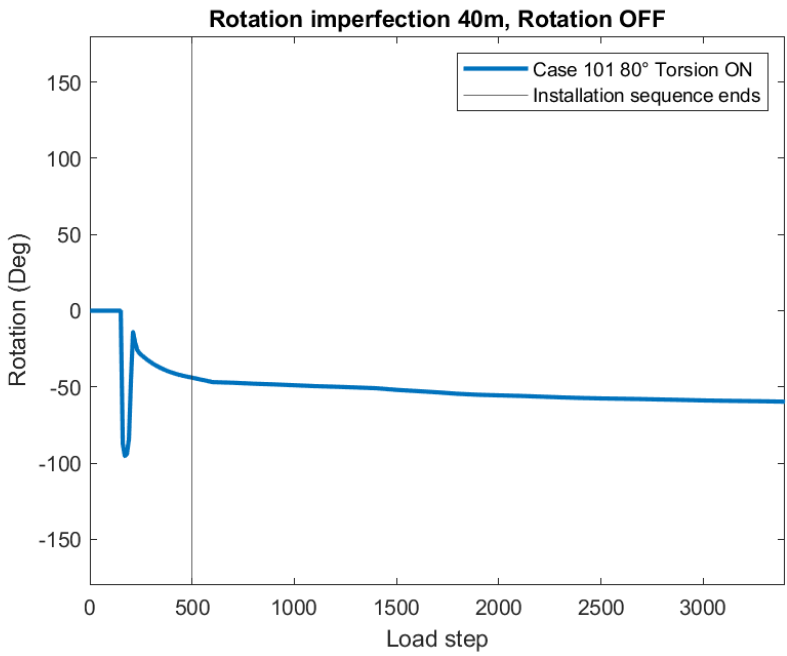


Figure 83: Rotation Case 101

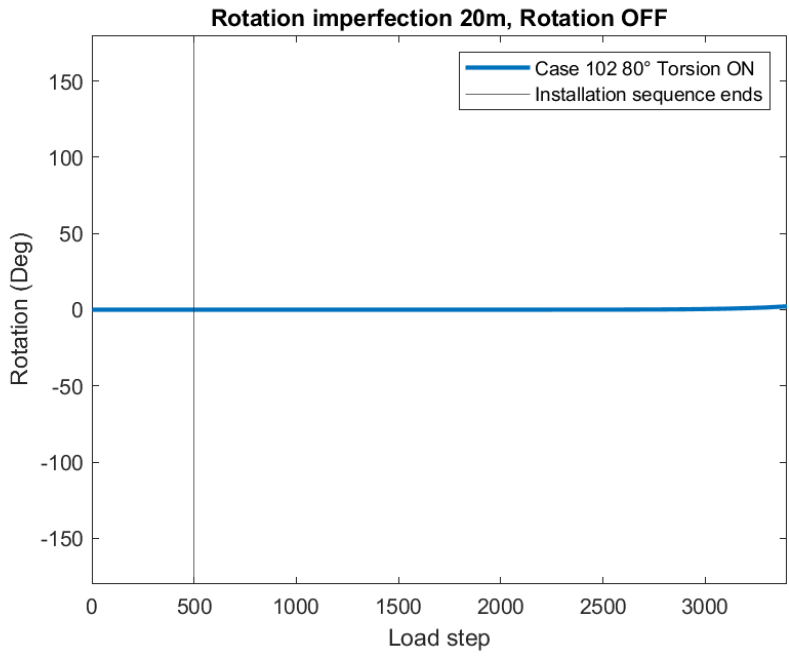


Figure 84: Rotation Case 102

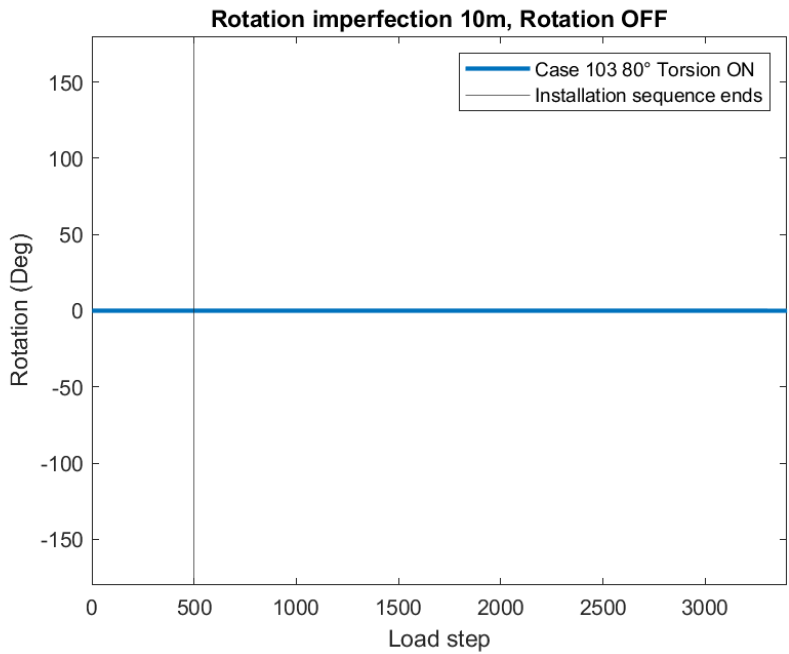


Figure 85: Rotation Case 103

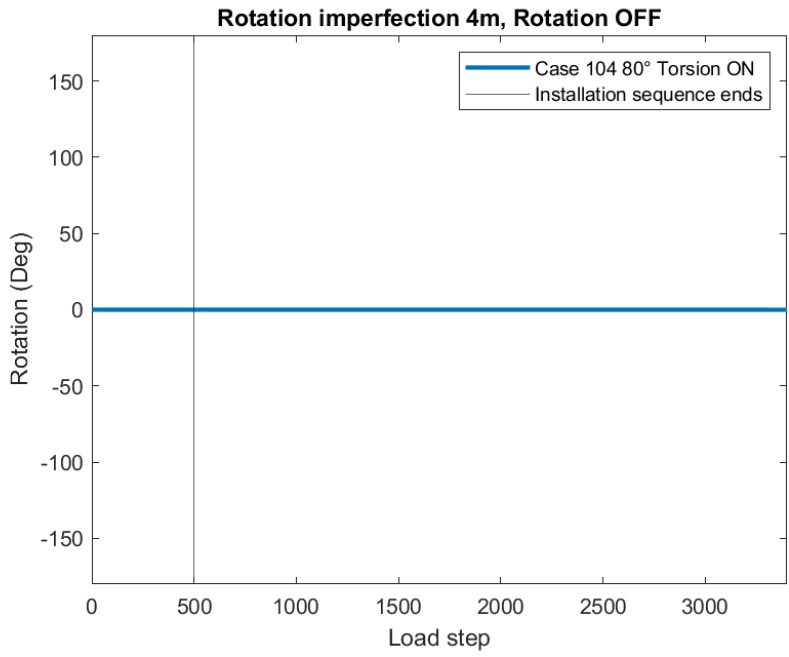


Figure 86: Rotation Case 104

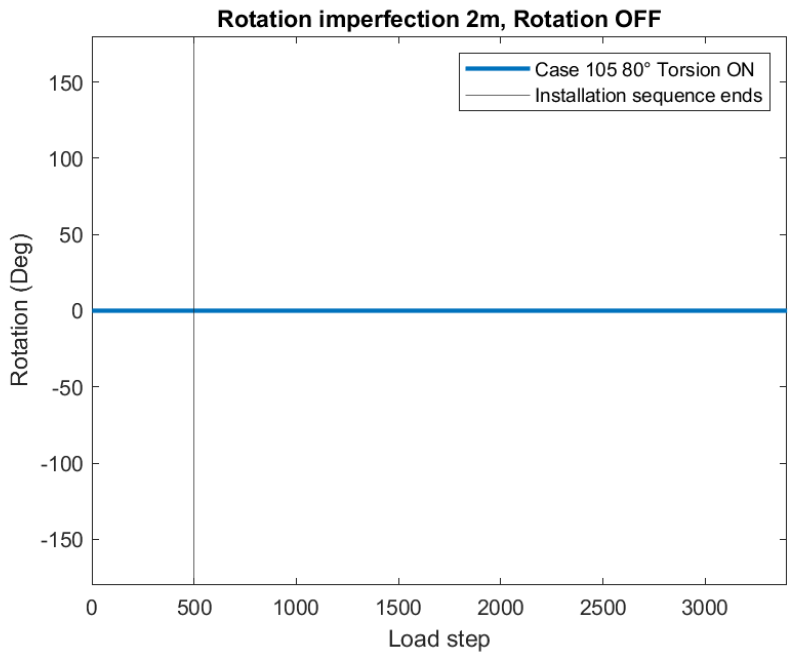


Figure 87: Rotation Case 105

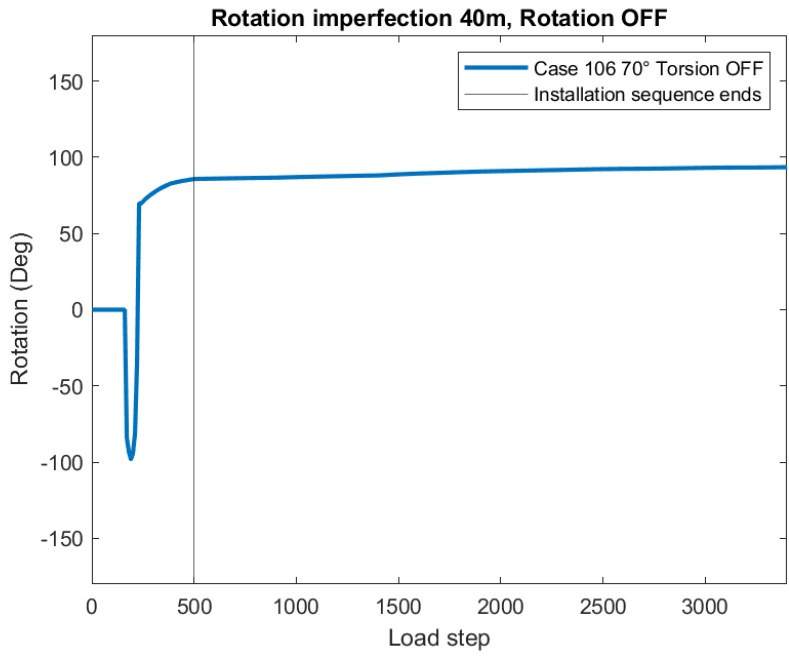


Figure 88: Rotation Case 106

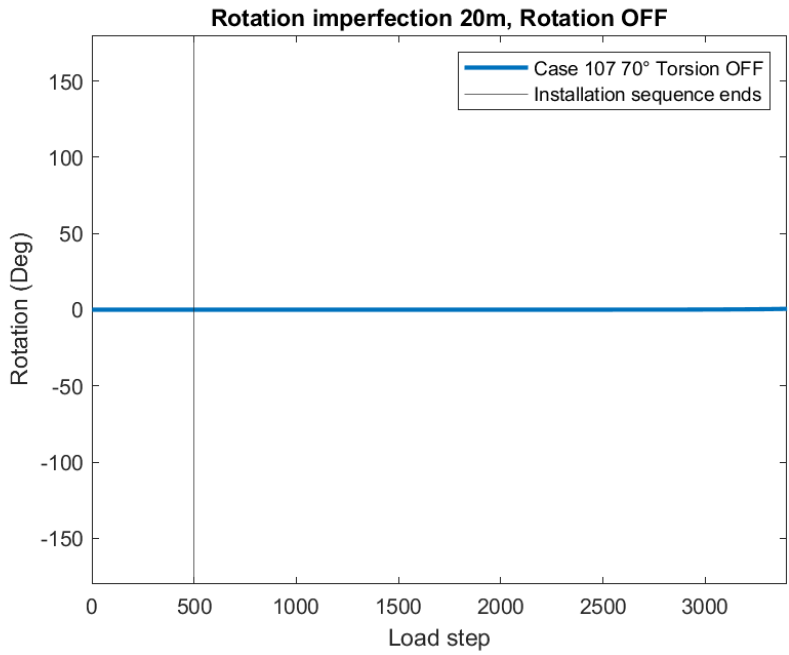


Figure 89: Rotation Case 107

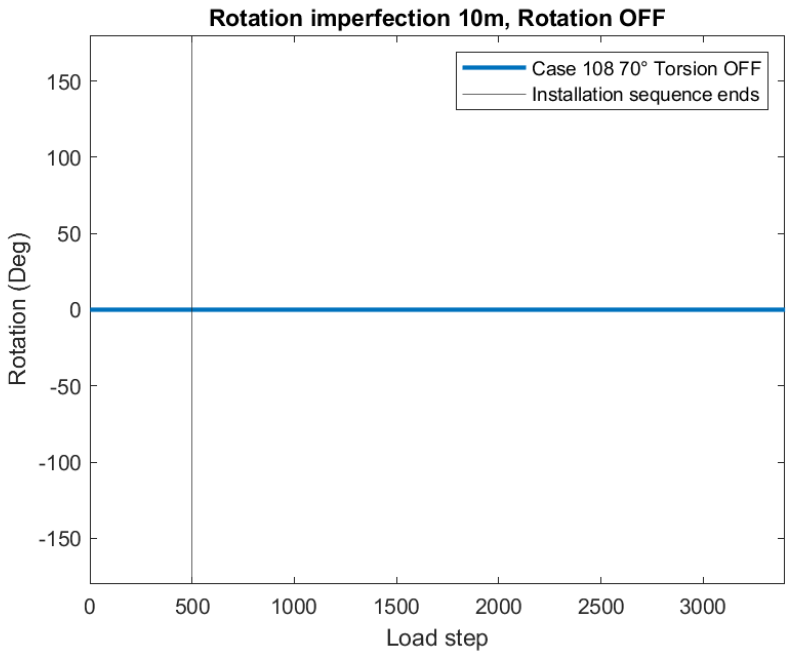


Figure 90: Rotation Case 108

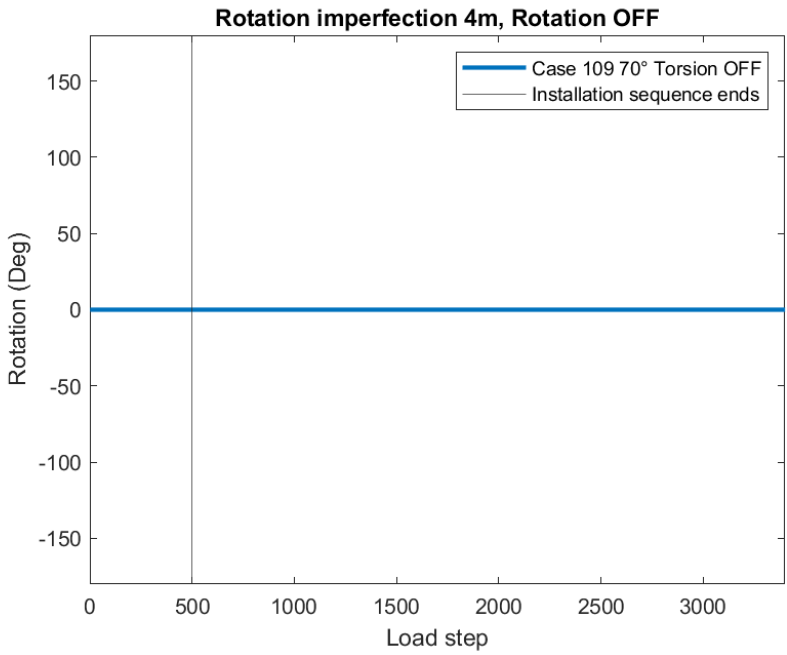


Figure 91: Rotation Case 109

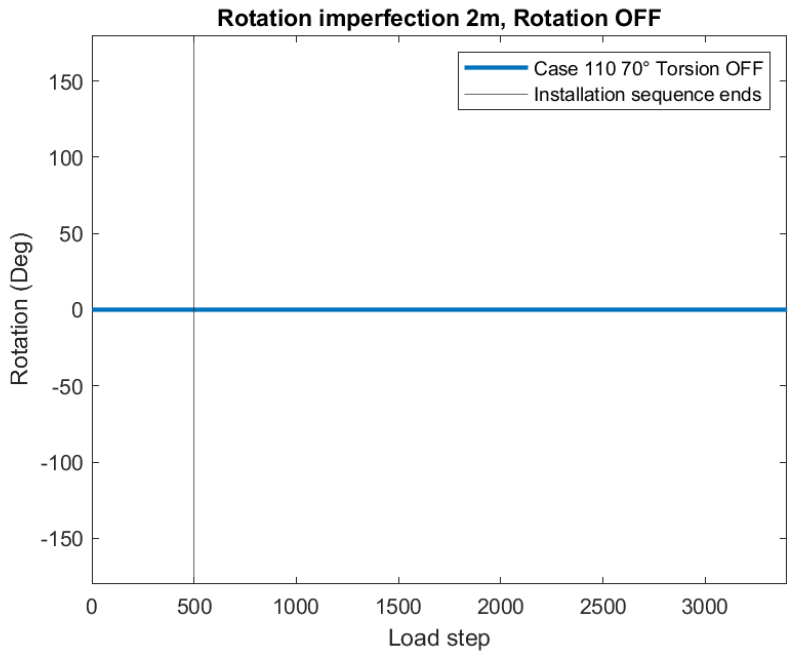


Figure 92: Rotation Case 110

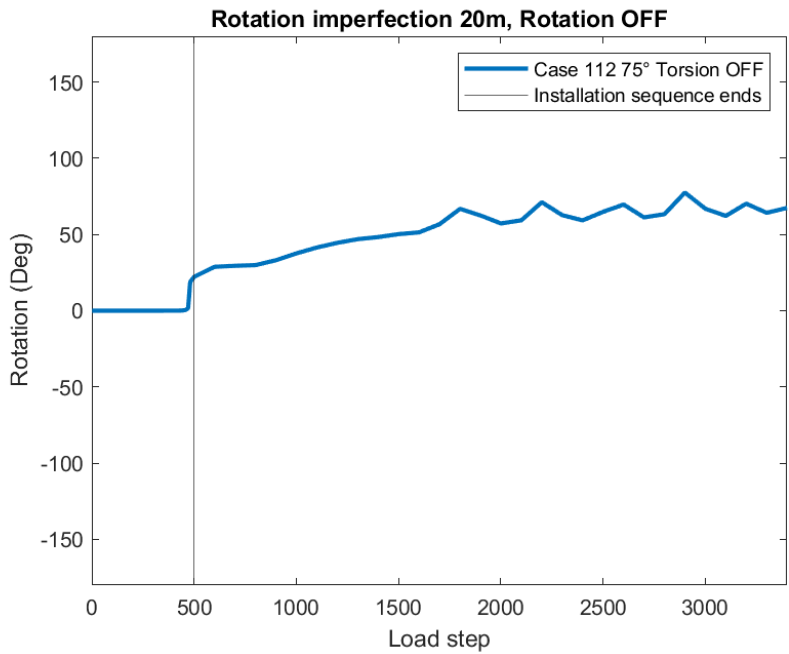


Figure 93: Rotation Case 112

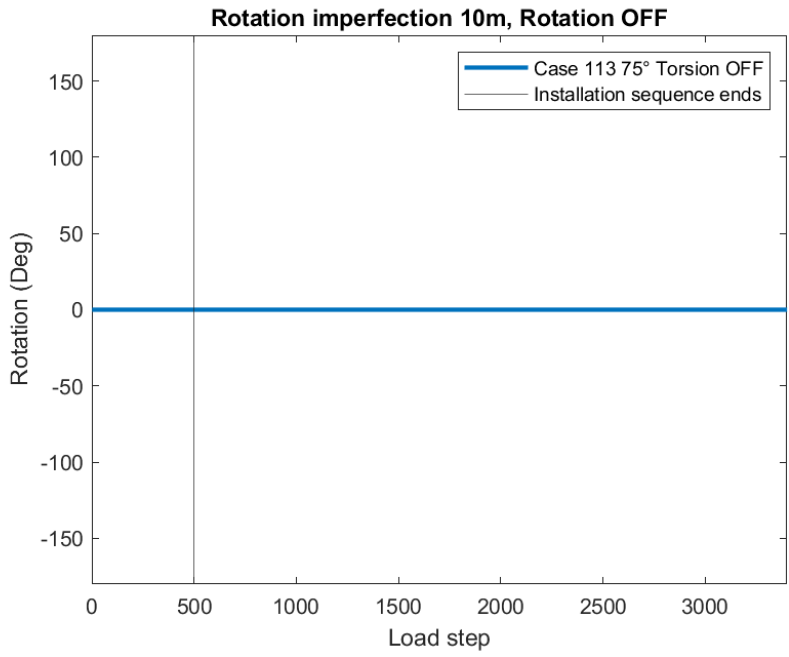


Figure 94: Rotation Case 113

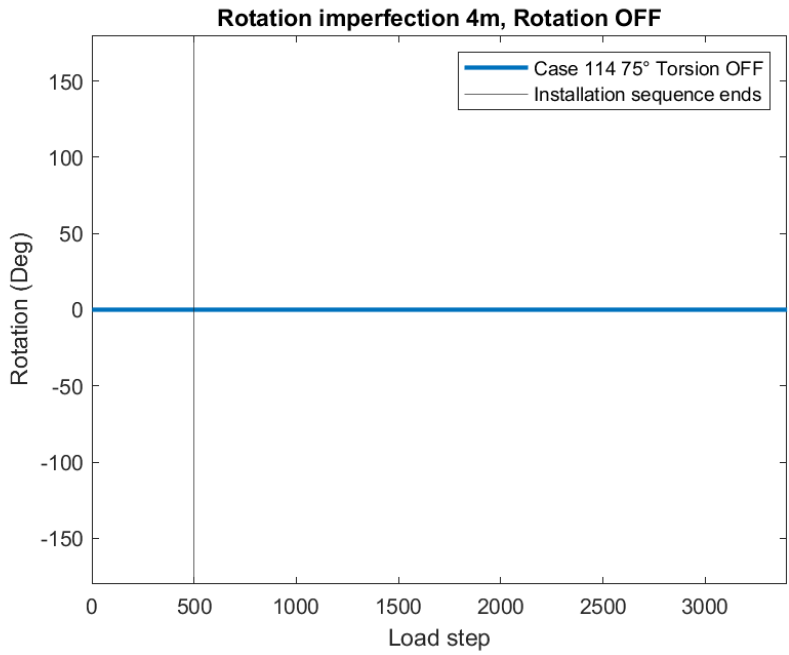


Figure 95: Rotation Case 114

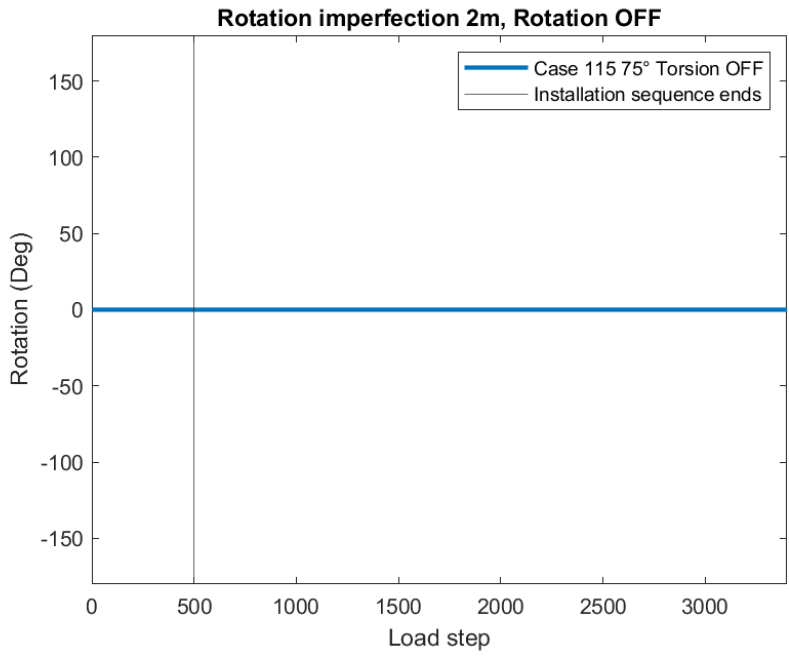


Figure 96: Rotation Case 115

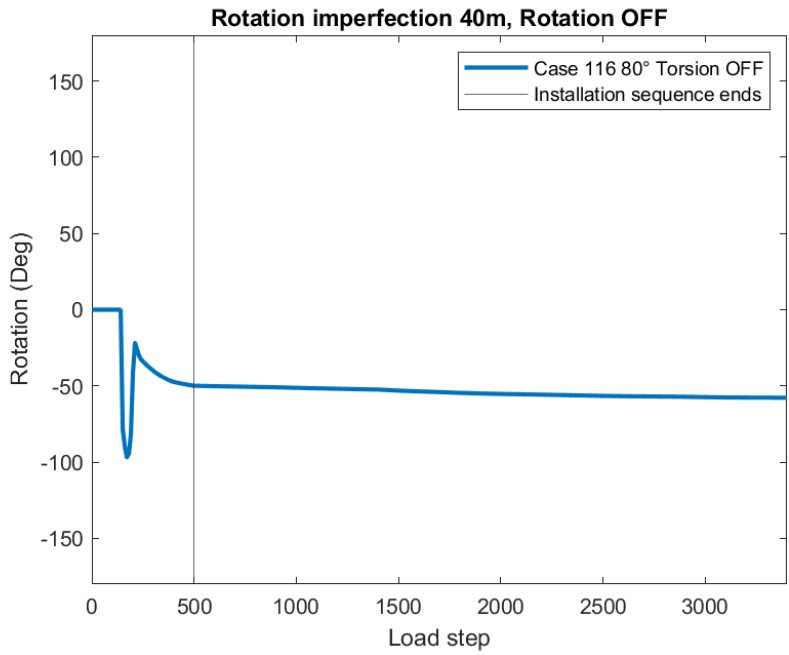


Figure 97: Rotation Case 116

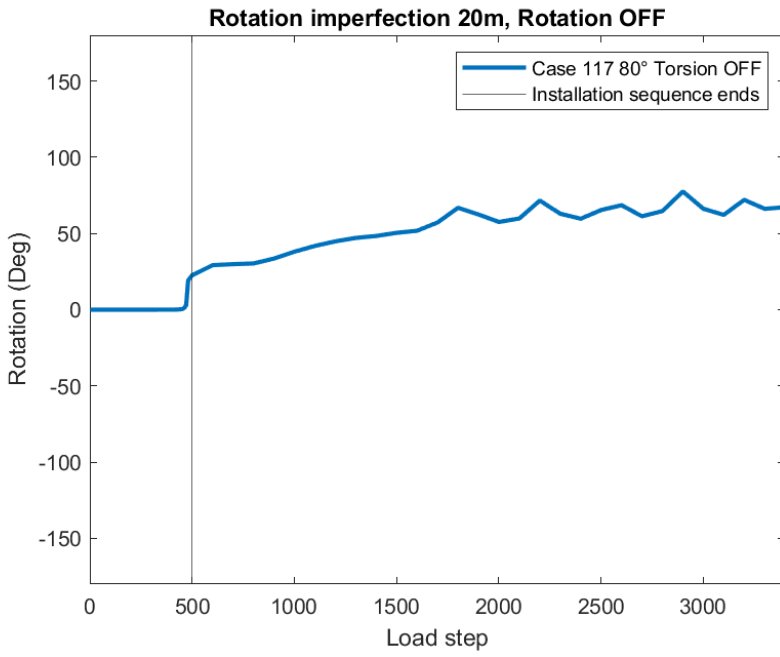


Figure 98: Rotation Case 117

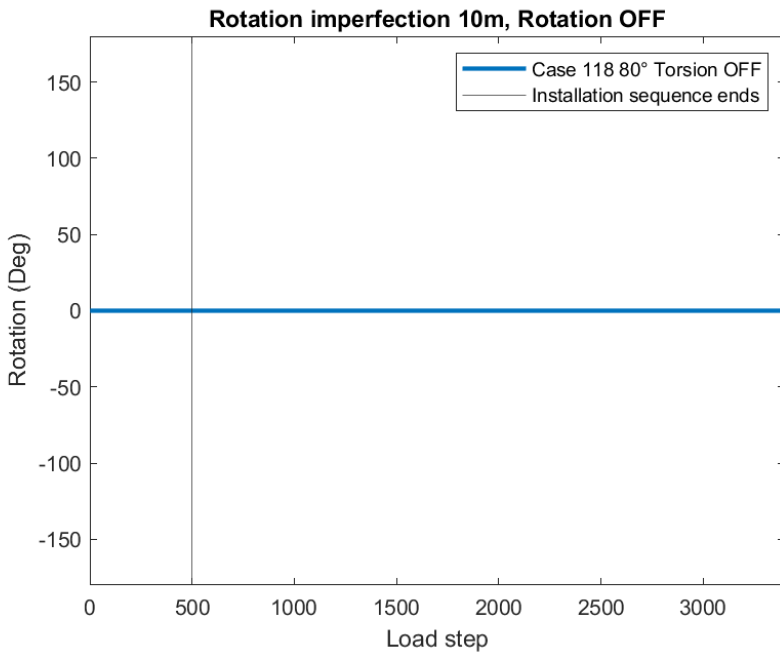


Figure 99: Rotation Case 118

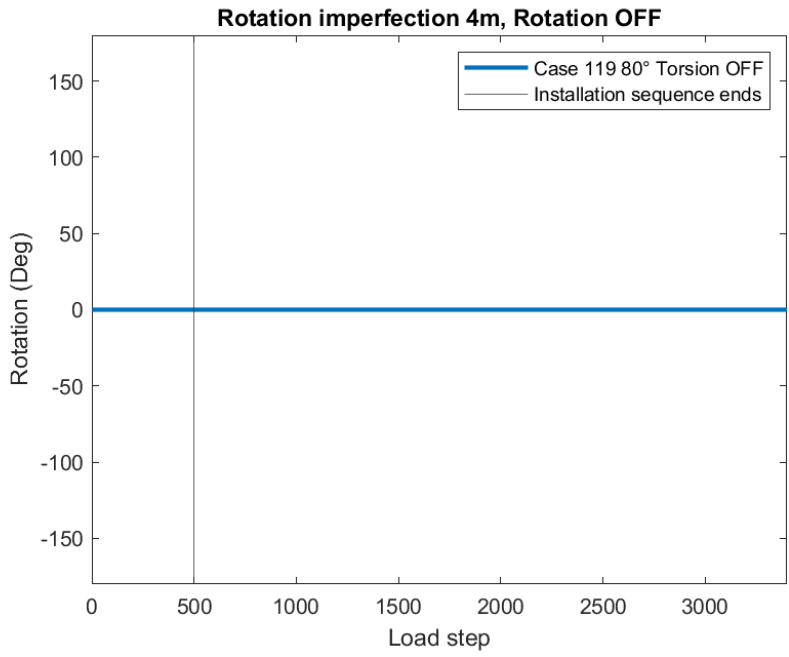


Figure 100: Rotation Case 119

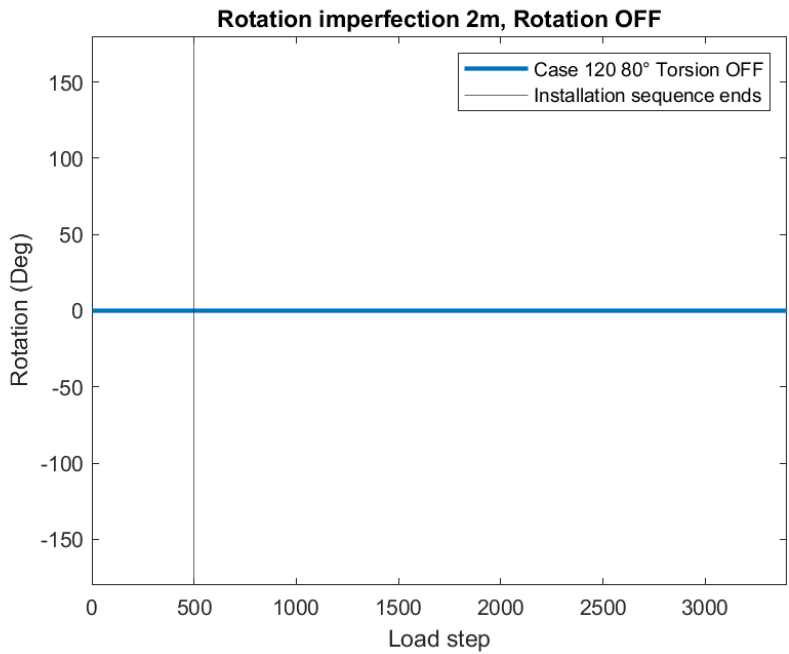


Figure 101: Rotation Case 120

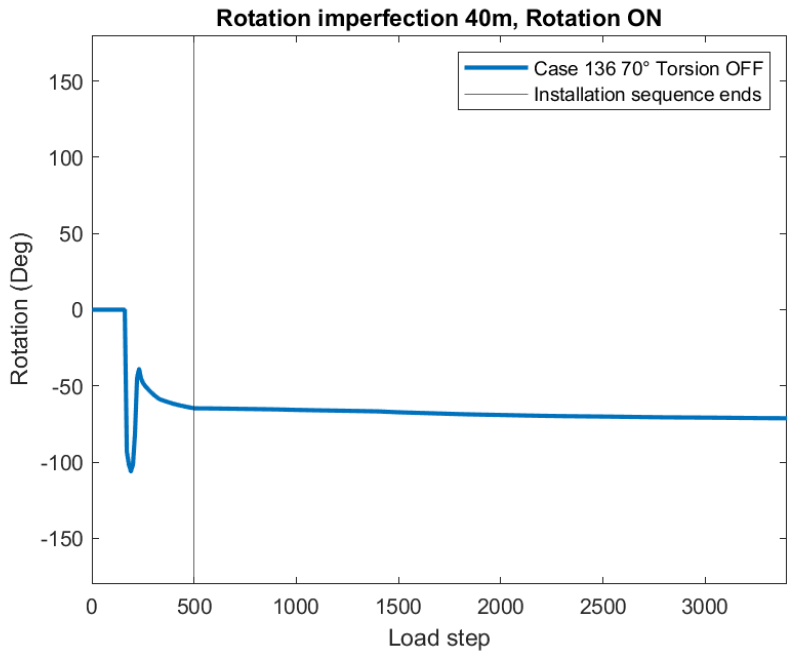


Figure 102: Rotation Case 136

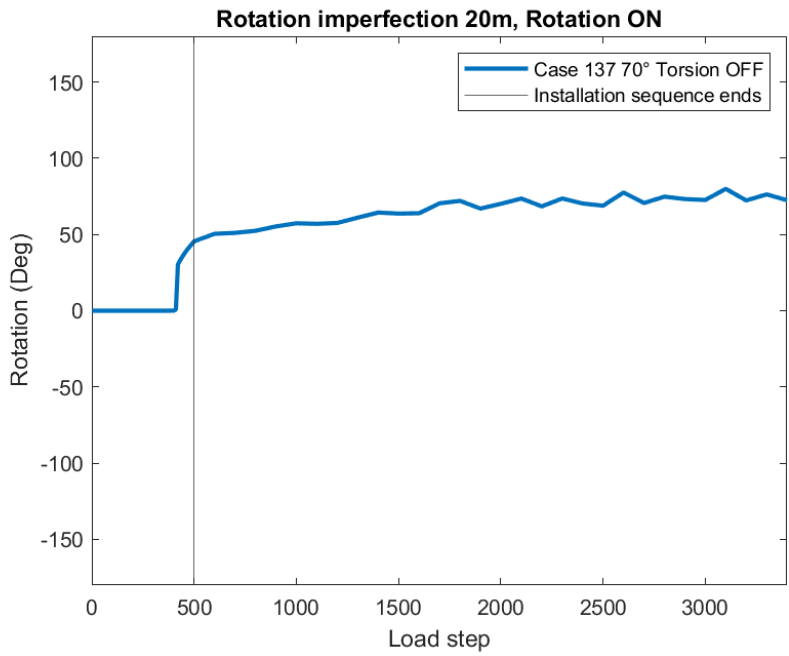


Figure 103: Rotation Case 137

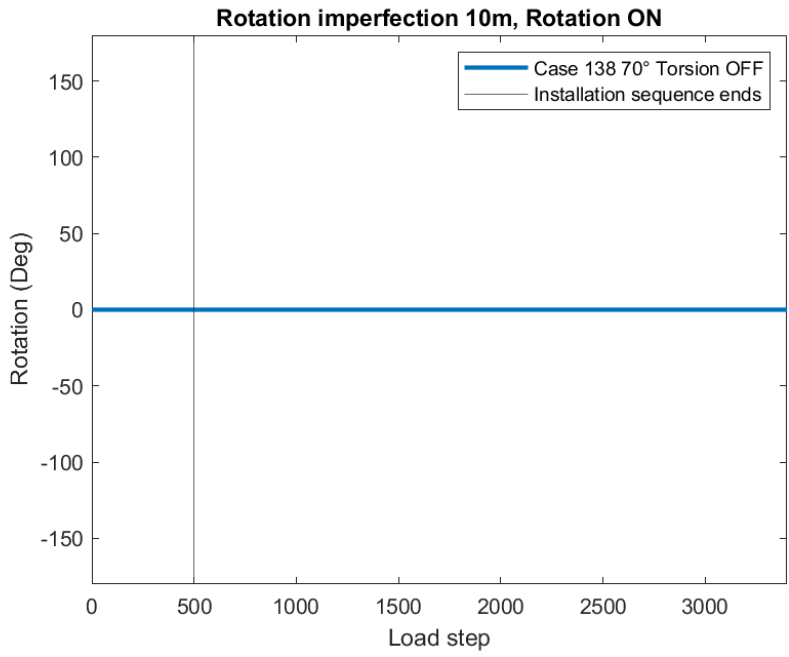


Figure 104: Rotation Case 138

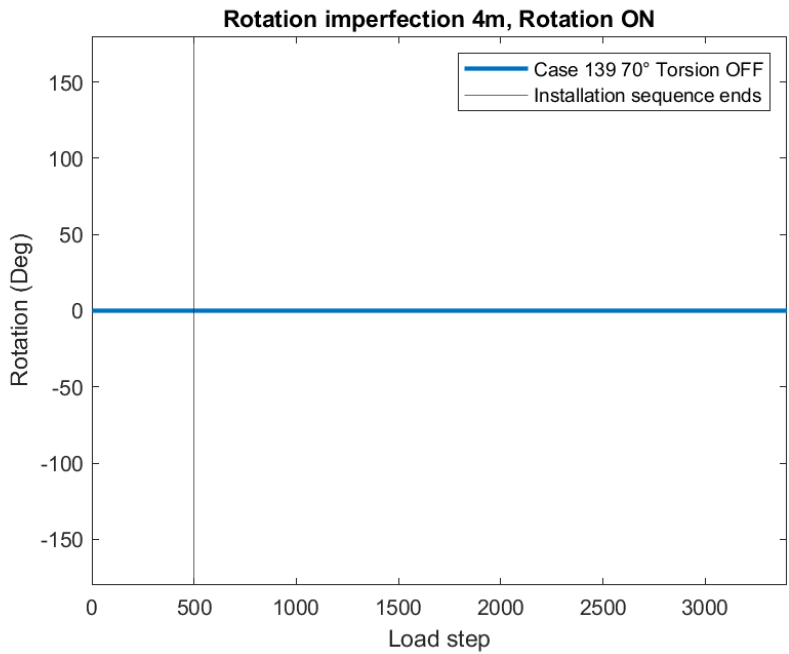


Figure 105: Rotation Case 139

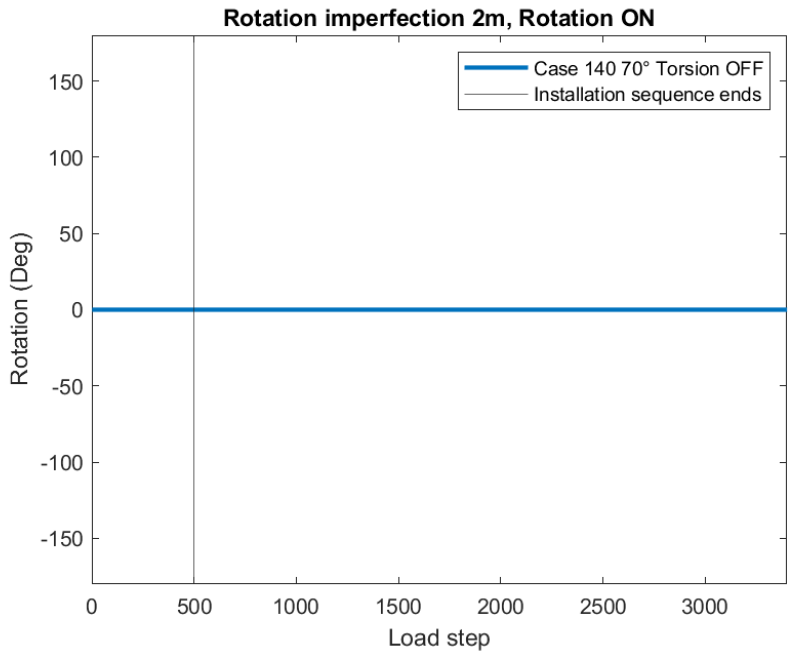


Figure 106: Rotation Case 140

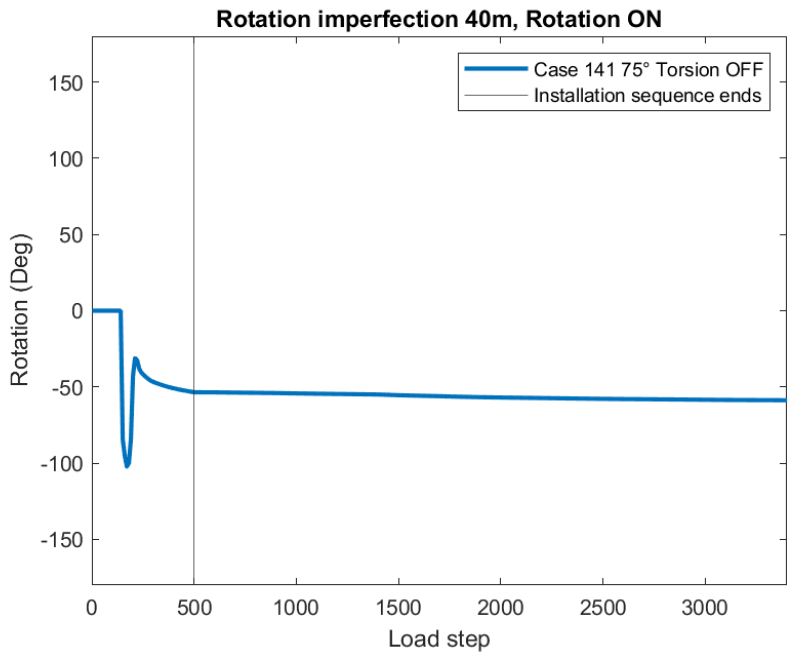


Figure 107: Rotation Case 141

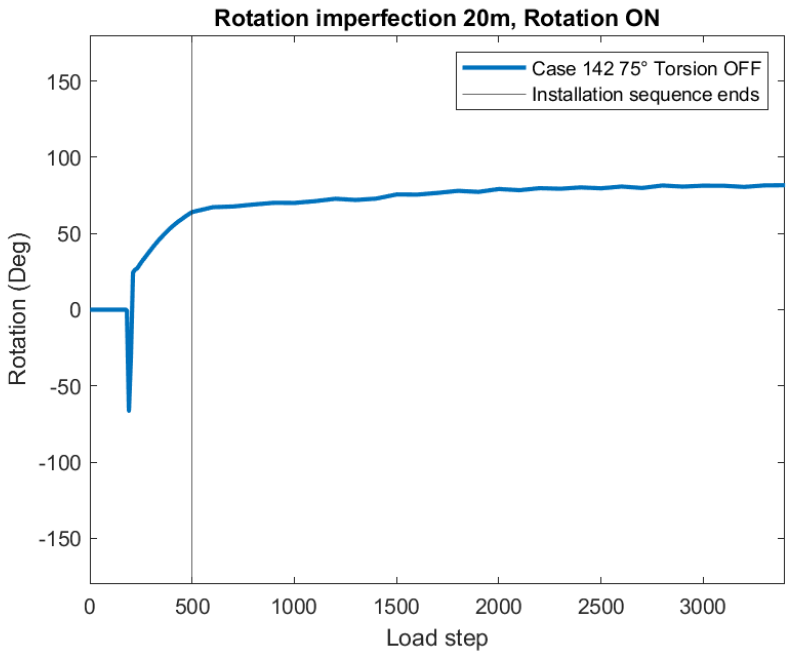


Figure 108: Rotation Case 142

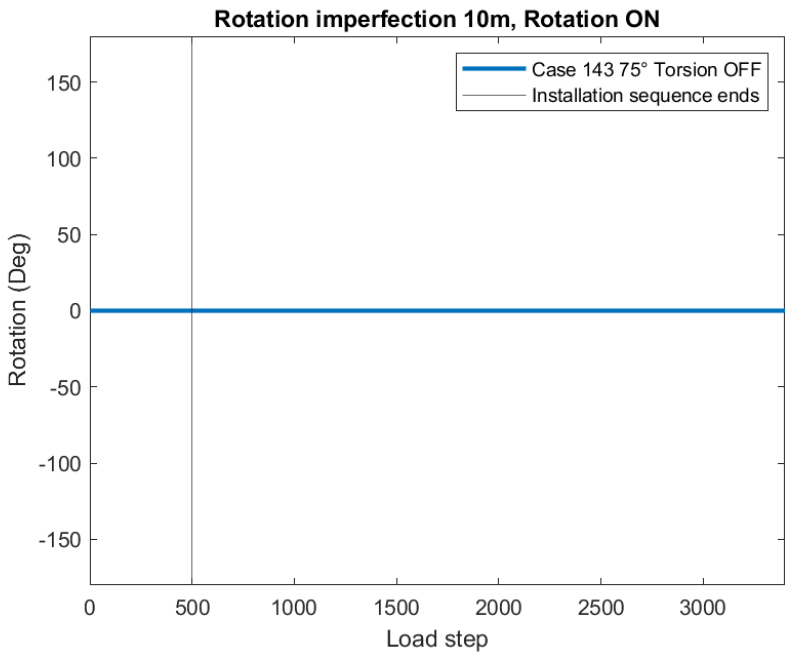


Figure 109: Rotation Case 143

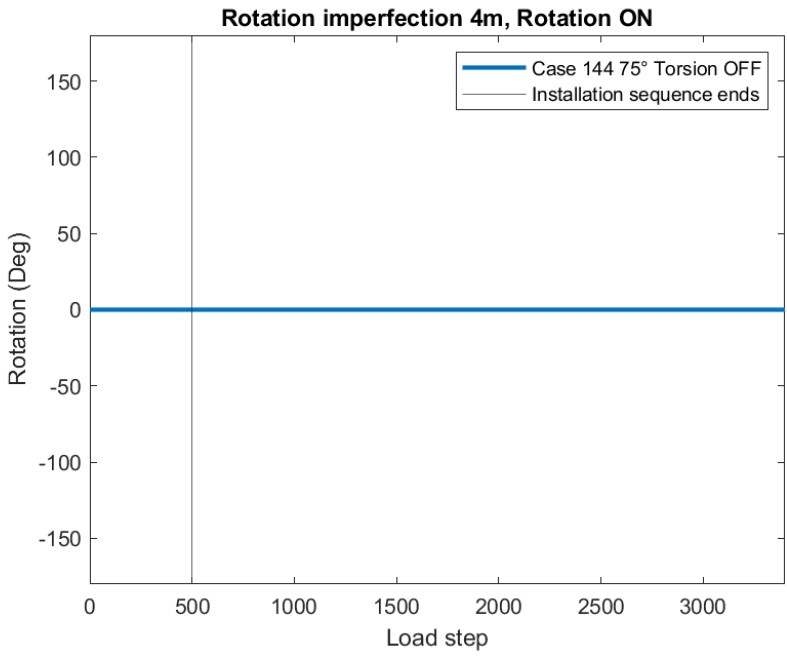


Figure 110: Rotation Case 144

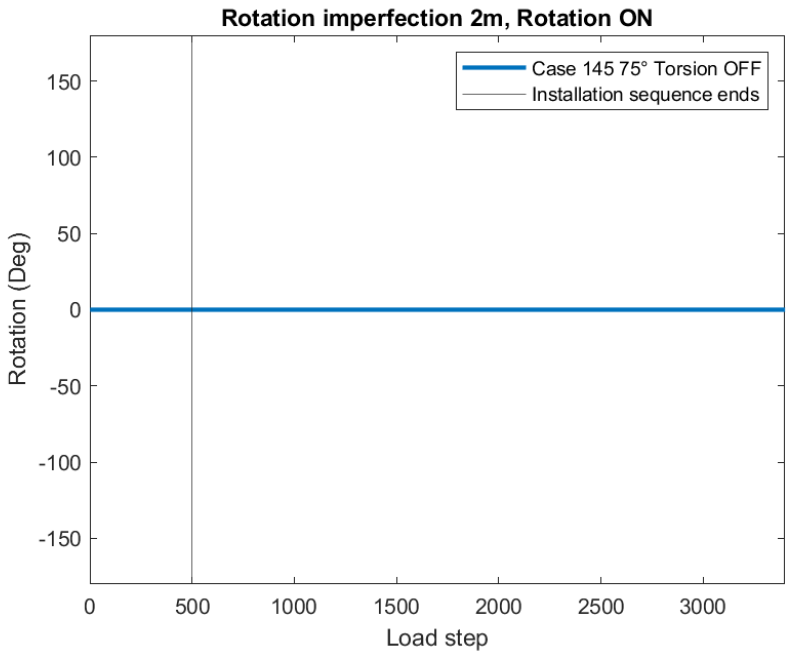


Figure 111: Rotation Case 145

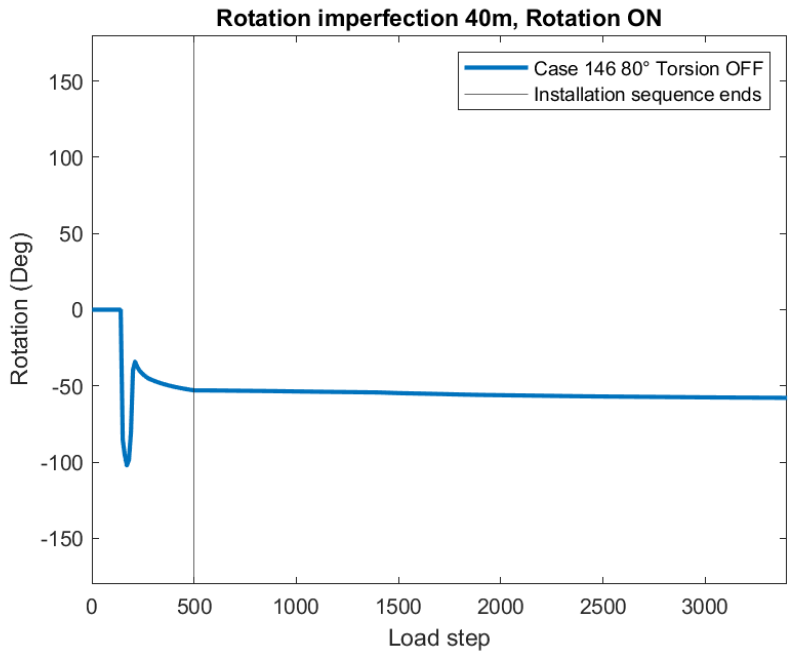


Figure 112: Rotation Case 146

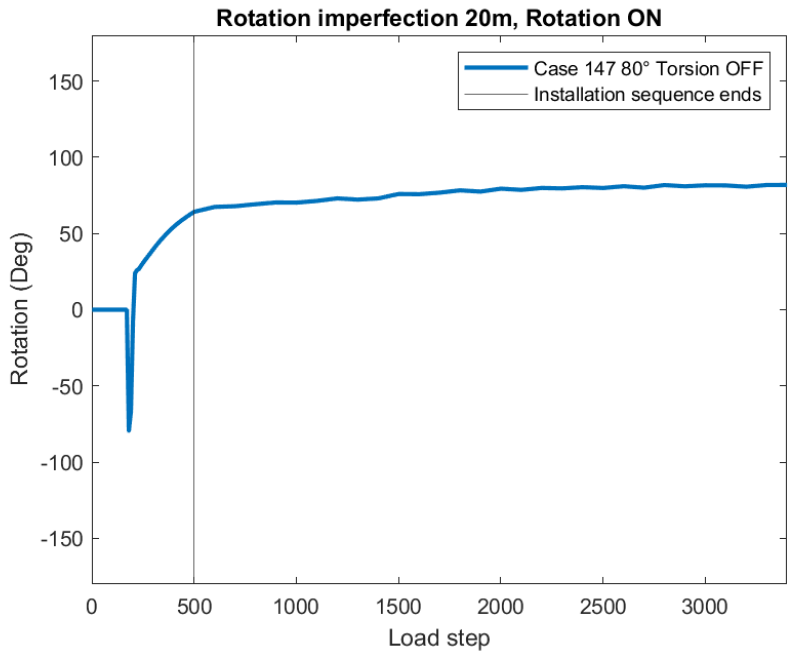


Figure 113: Rotation Case 147

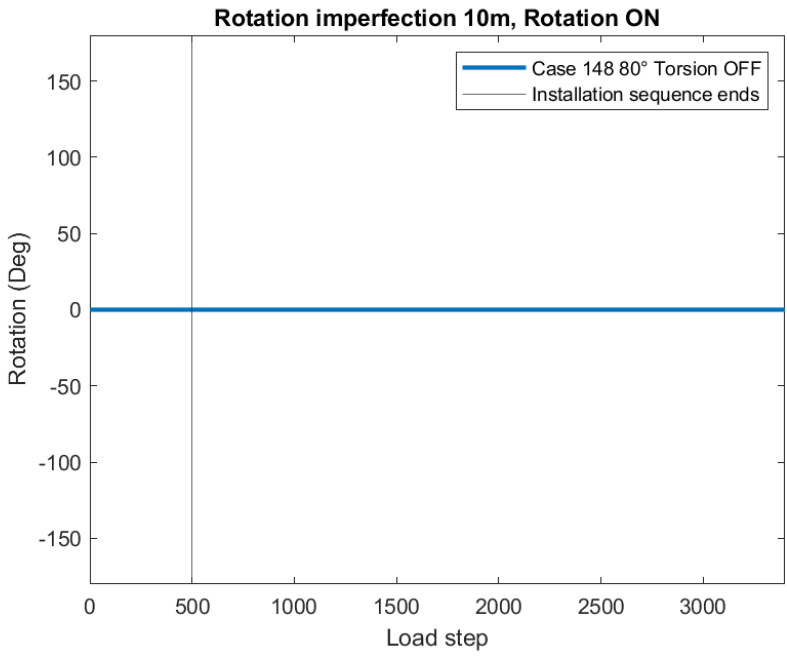


Figure 114: Rotation Case 148

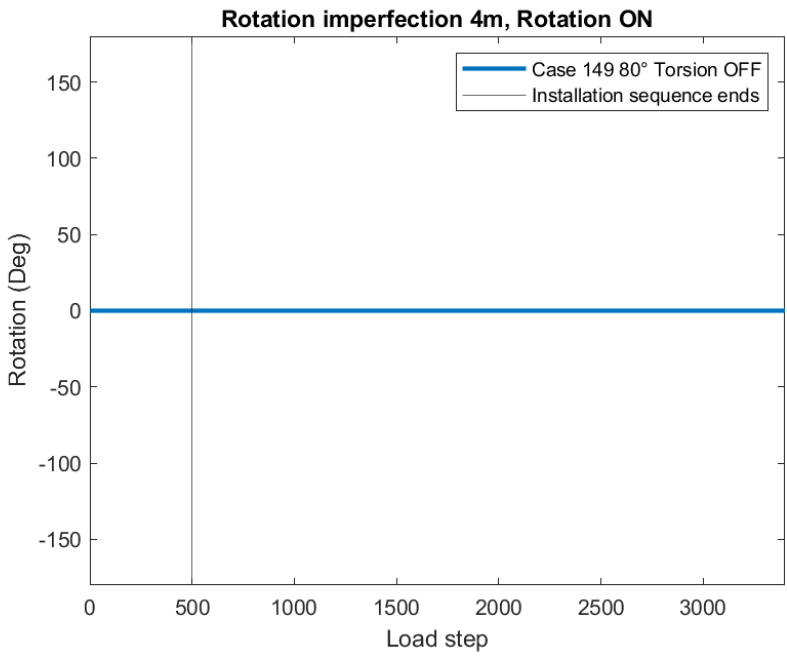


Figure 115: Rotation Case 149

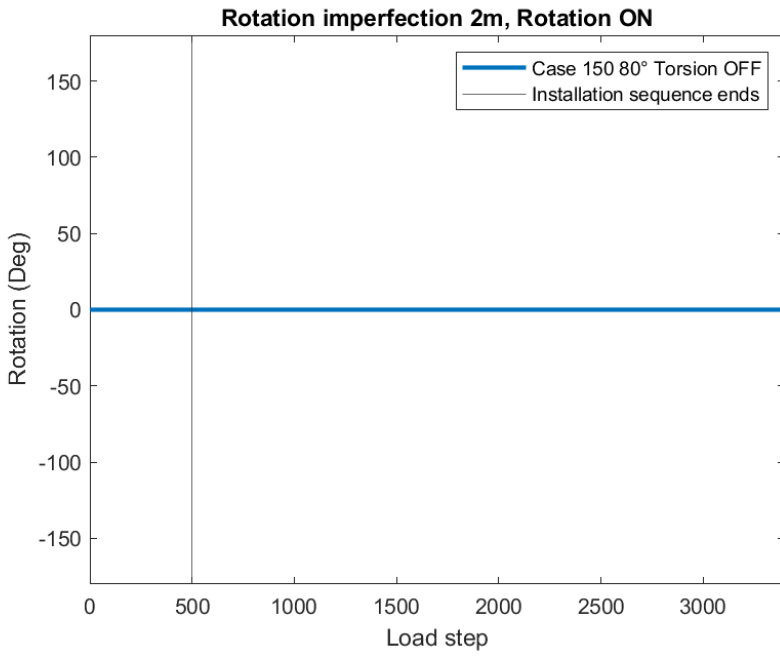


Figure 116: Rotation Case 150

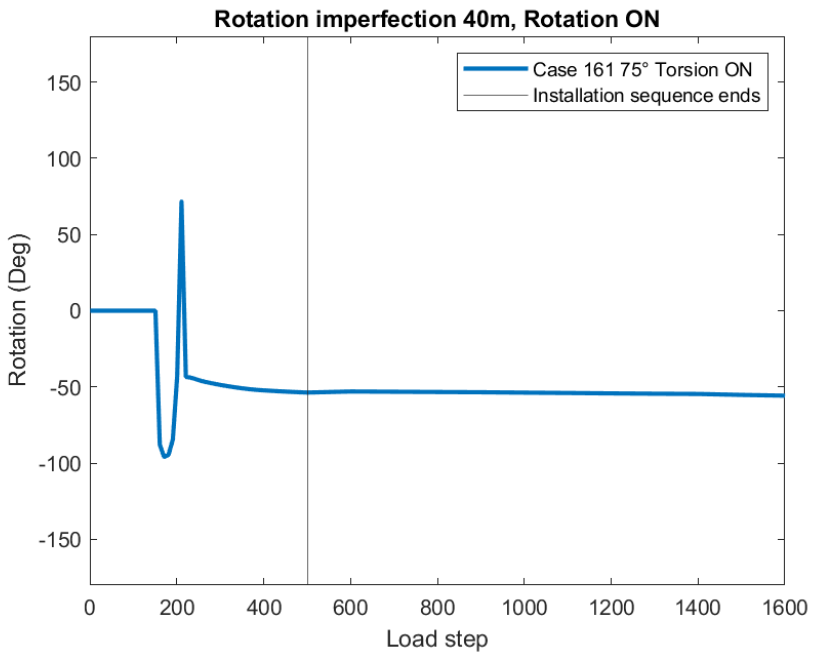


Figure 117: Rotation Case 161

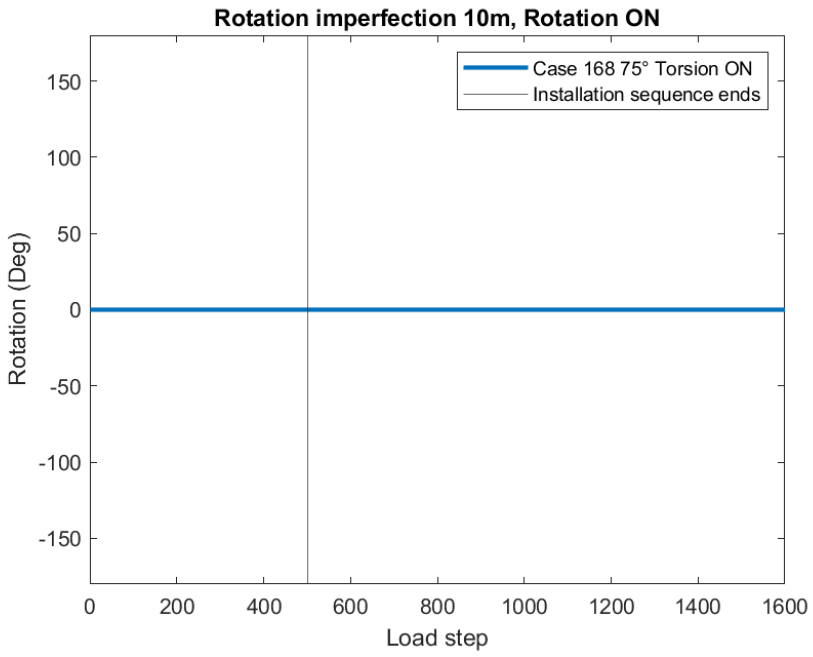


Figure 118: Rotation Case 168

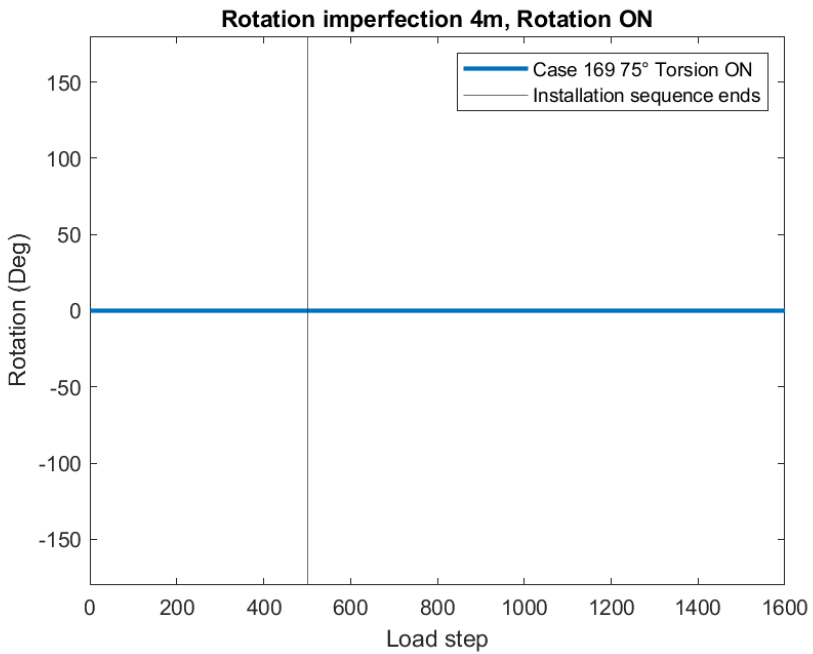


Figure 119: Rotation Case 169

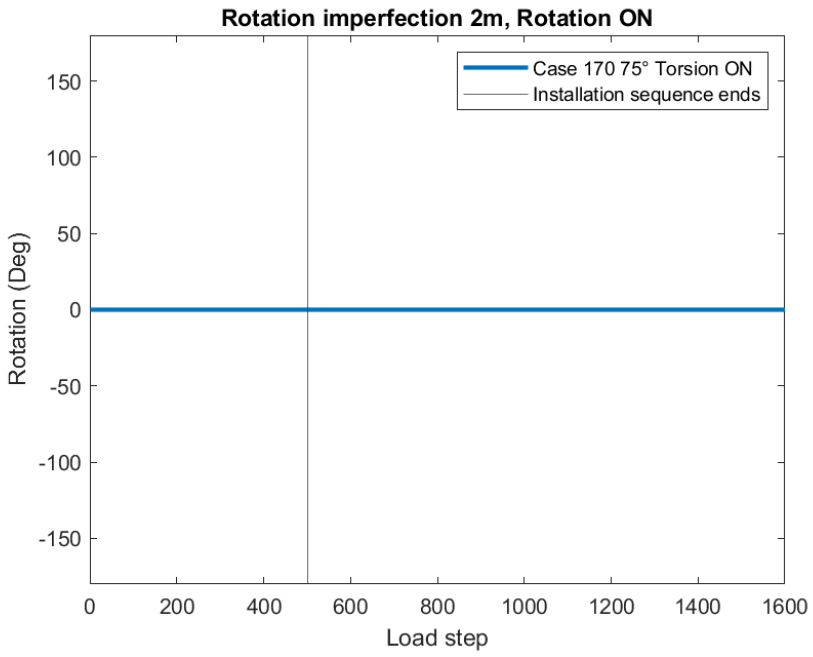


Figure 120: Rotation Case 170

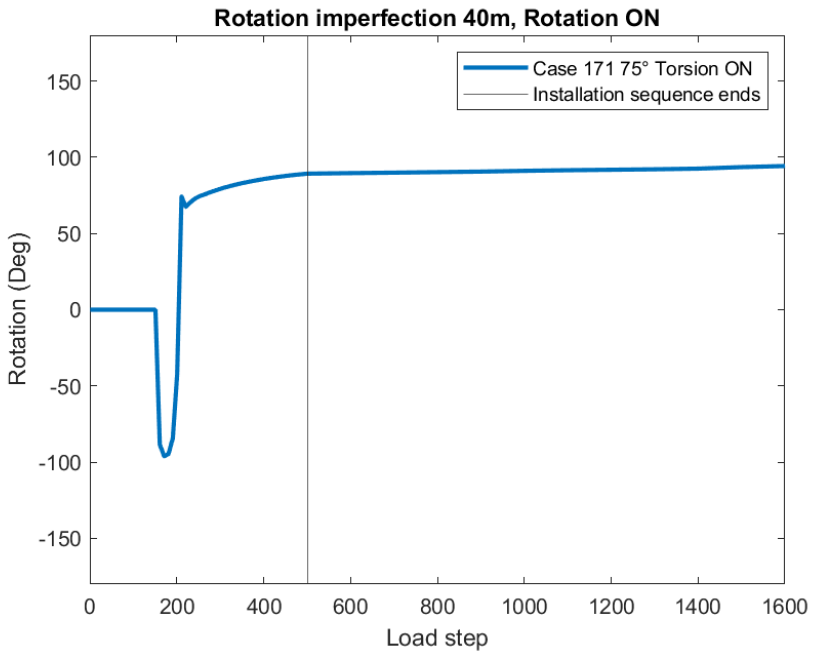


Figure 121: Rotation Case 171

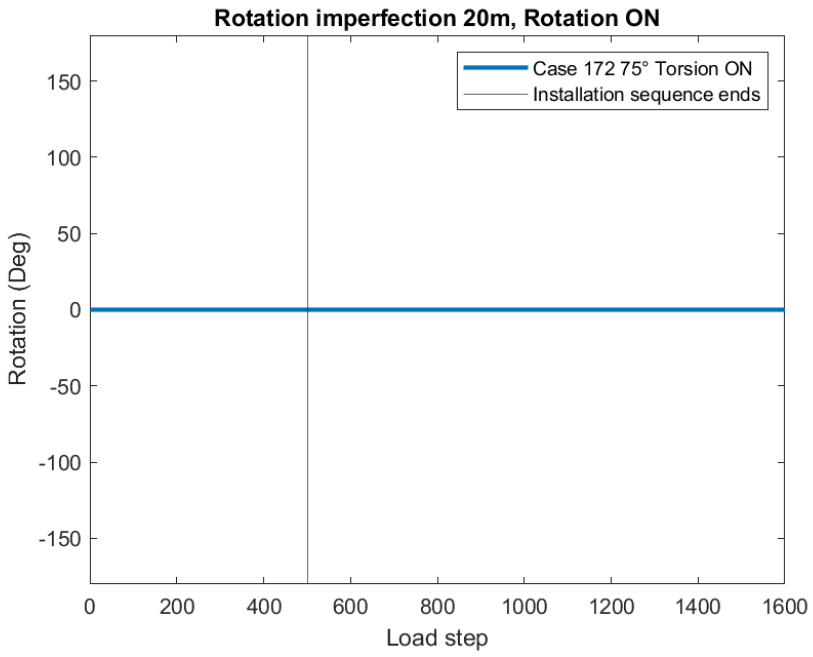


Figure 122: Rotation Case 172

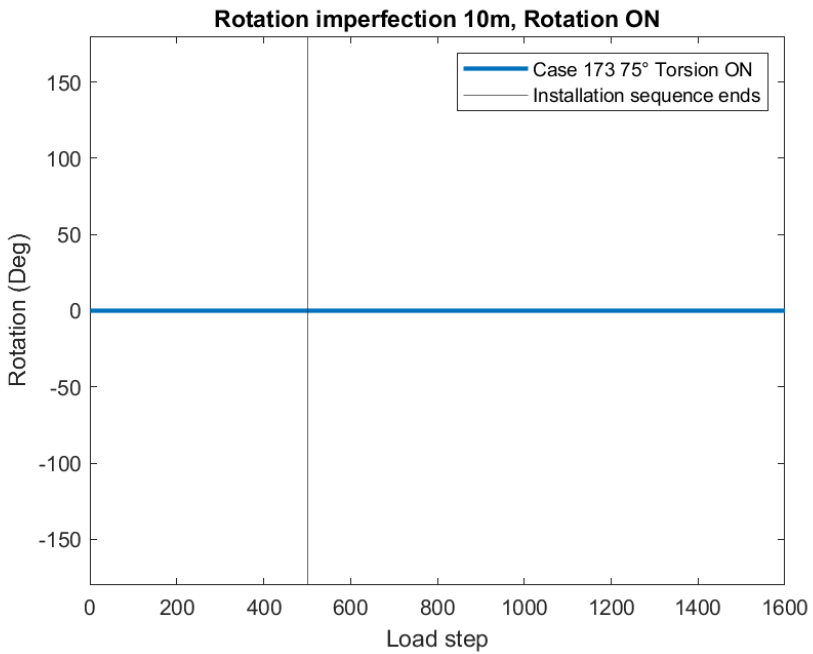


Figure 123: Rotation Case 173

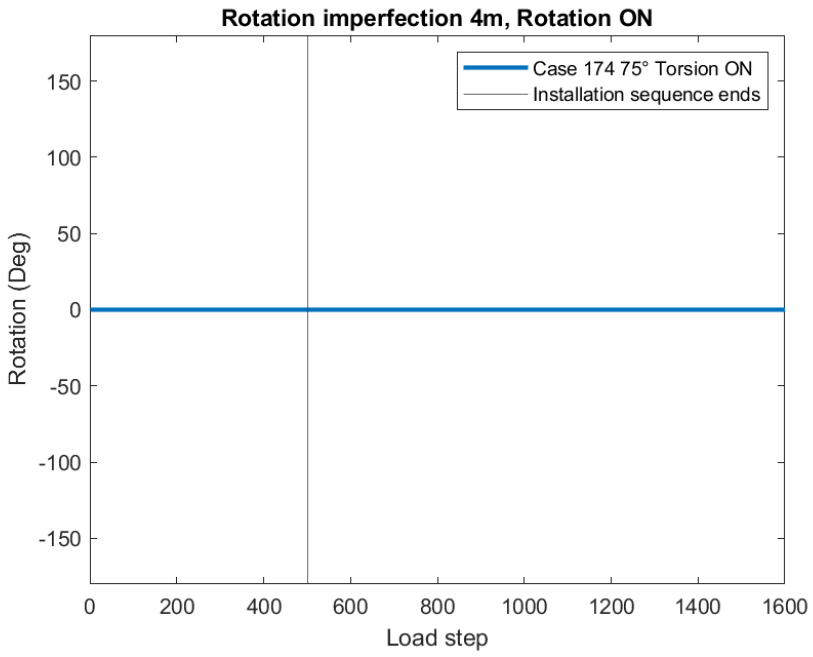


Figure 124: Rotation Case 174

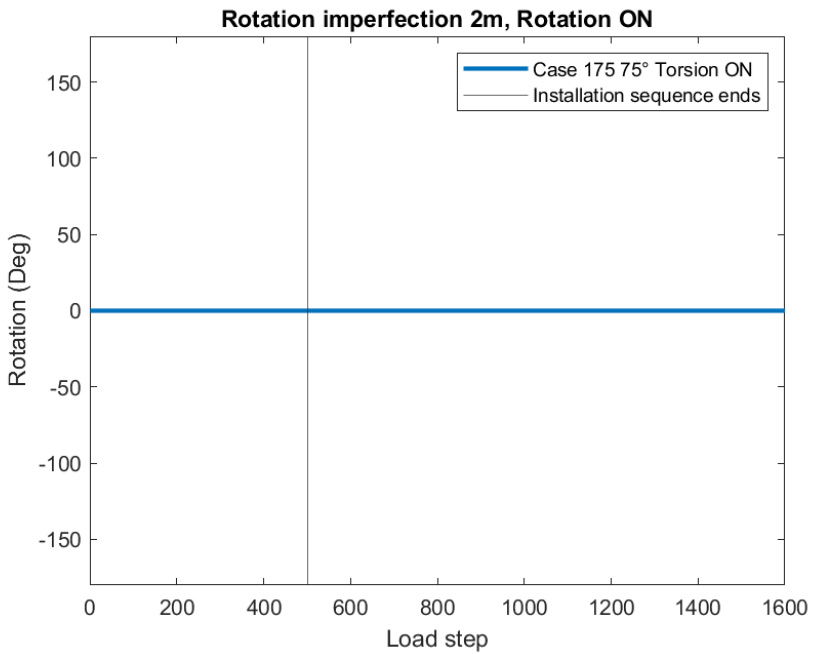


Figure 125: Rotation Case 175

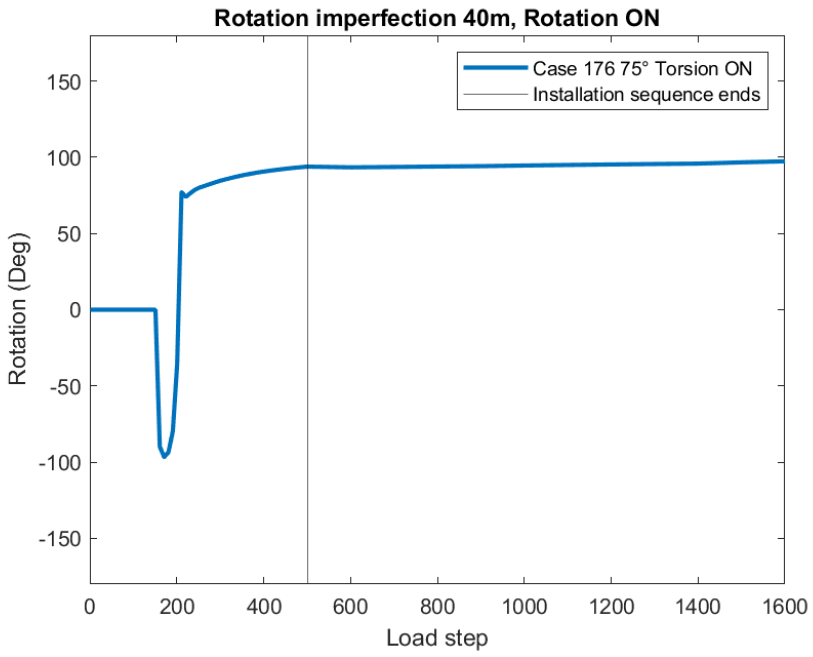


Figure 126: Rotation Case 176

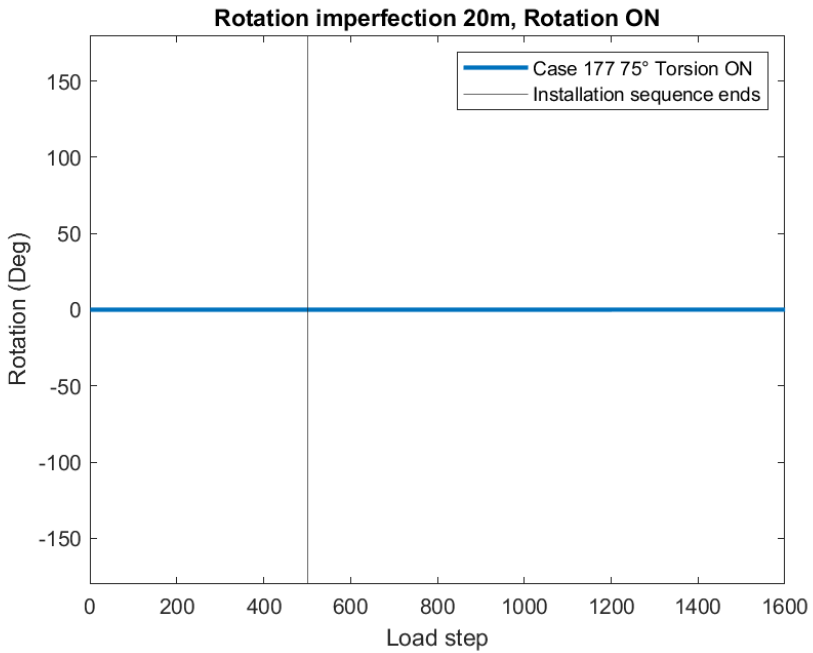


Figure 127: Rotation Case 177

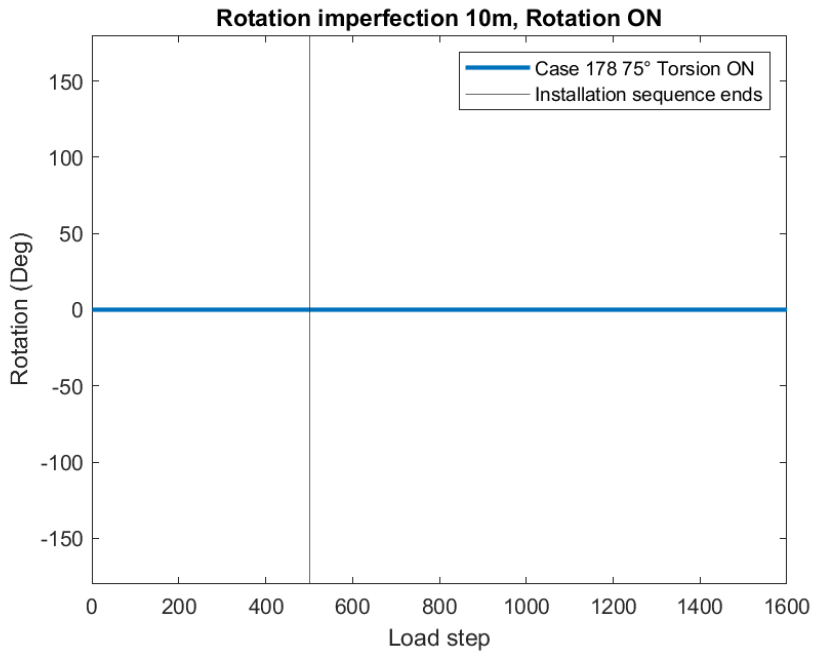


Figure 128: Rotation Case 178

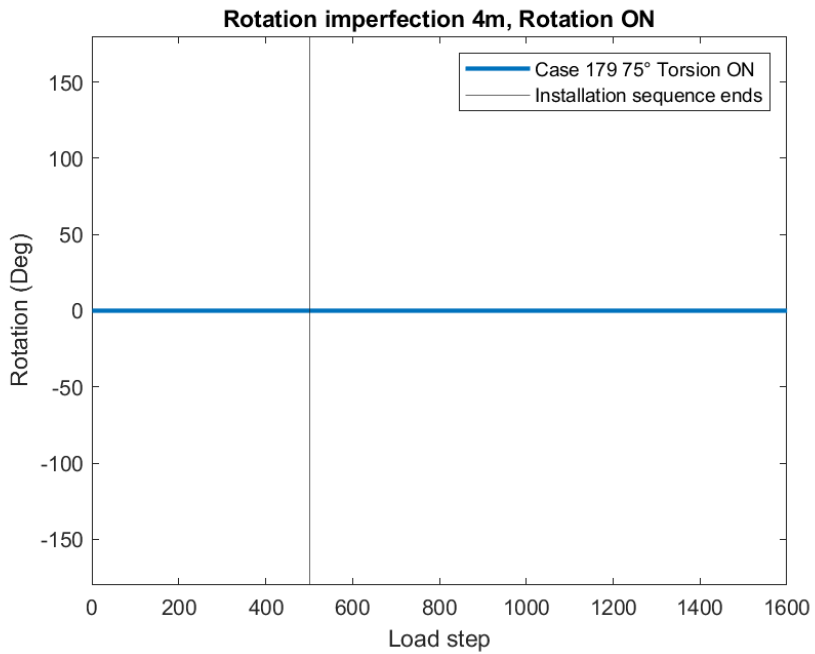


Figure 129: Rotation Case 179

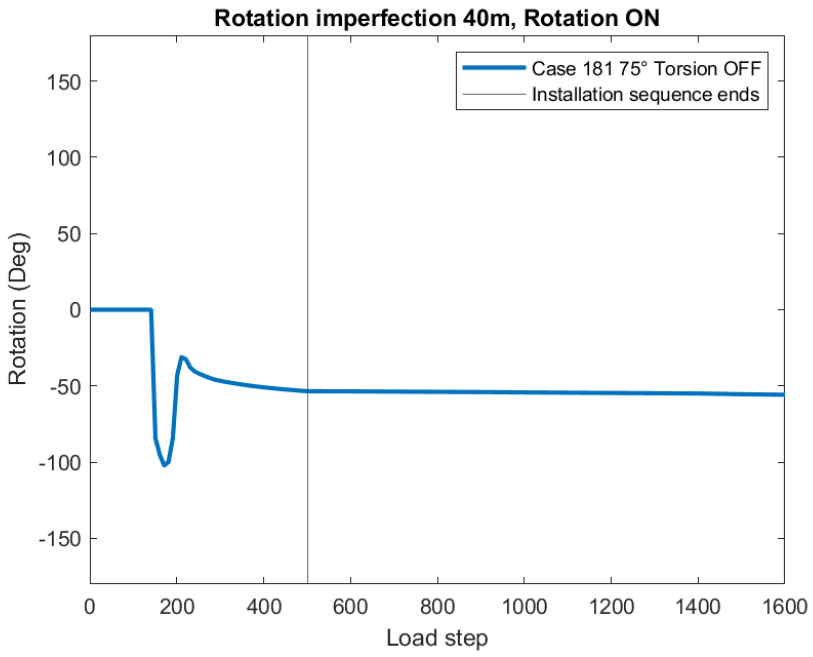


Figure 130: Rotation Case 181

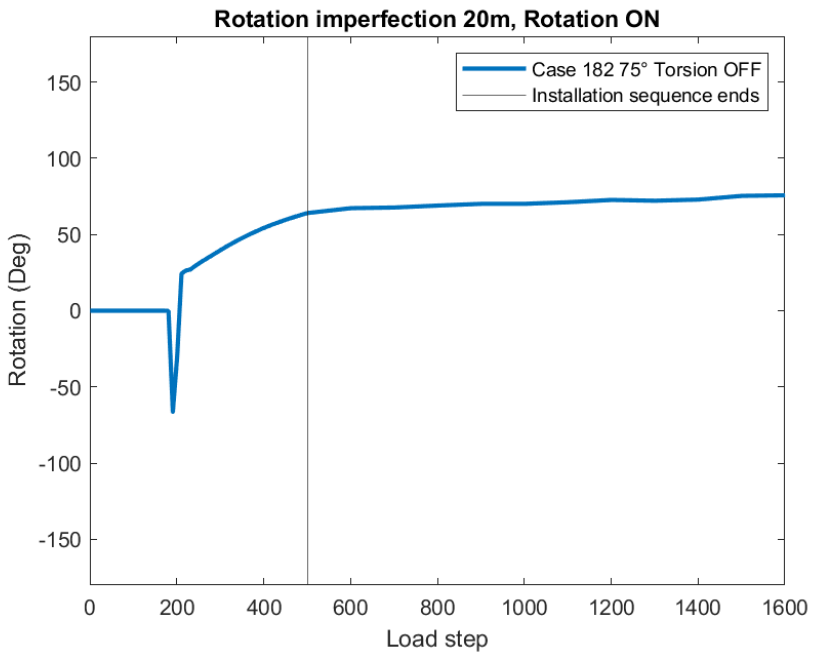


Figure 131: Rotation Case 182

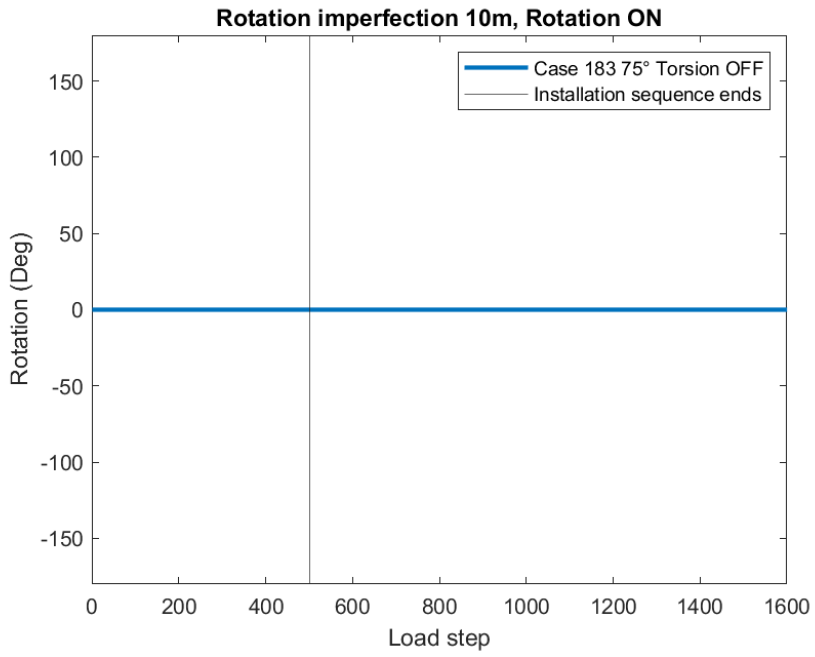


Figure 132: Rotation Case 183

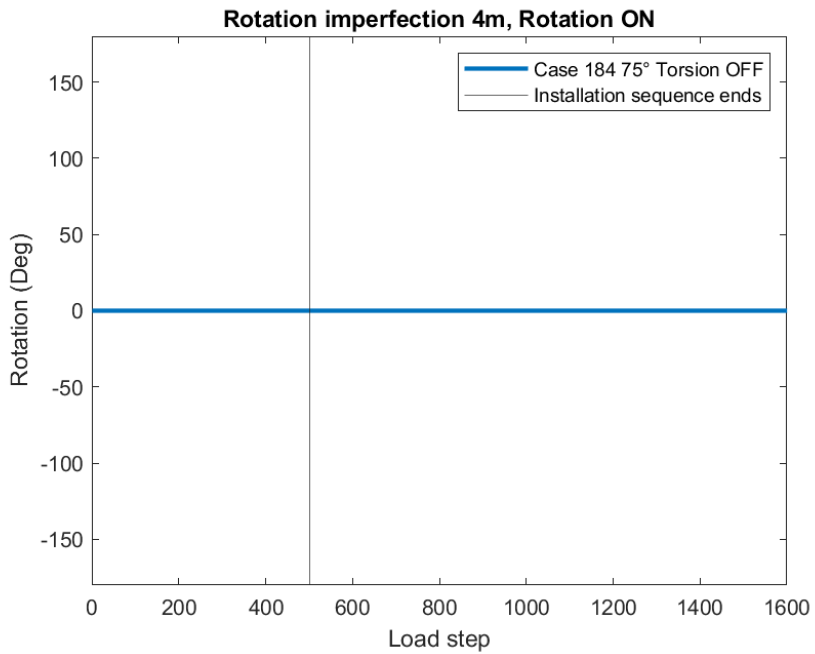


Figure 133: Rotation Case 184

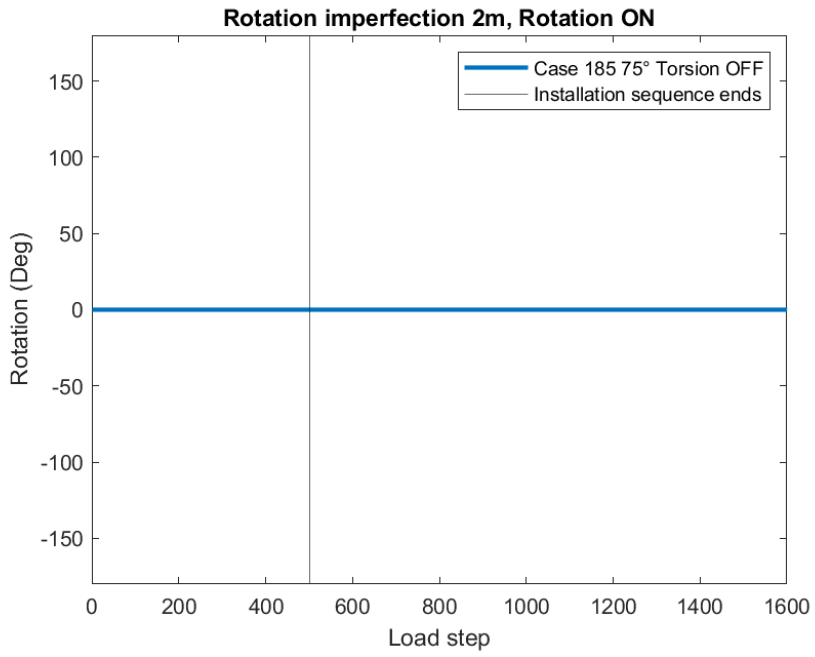


Figure 134: Rotation Case 185

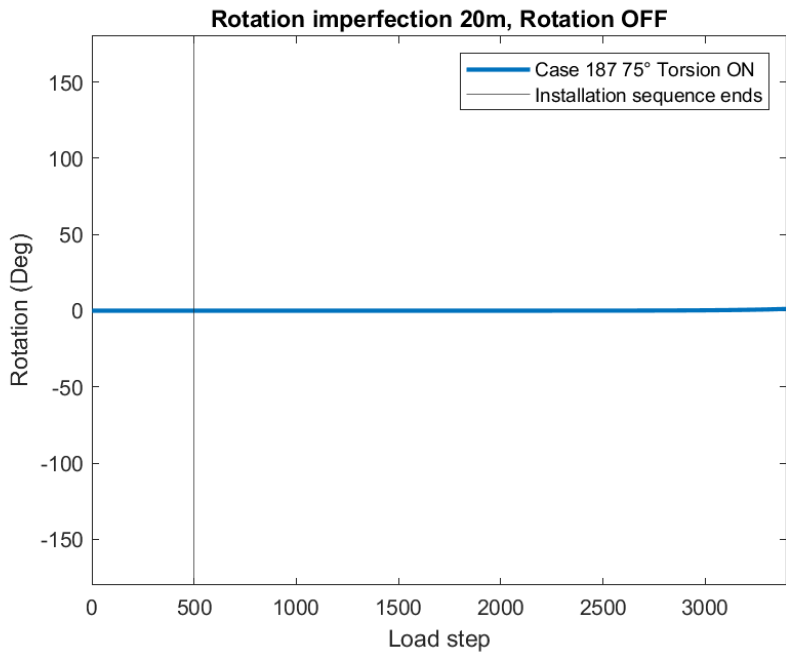


Figure 135: Rotation Case 187

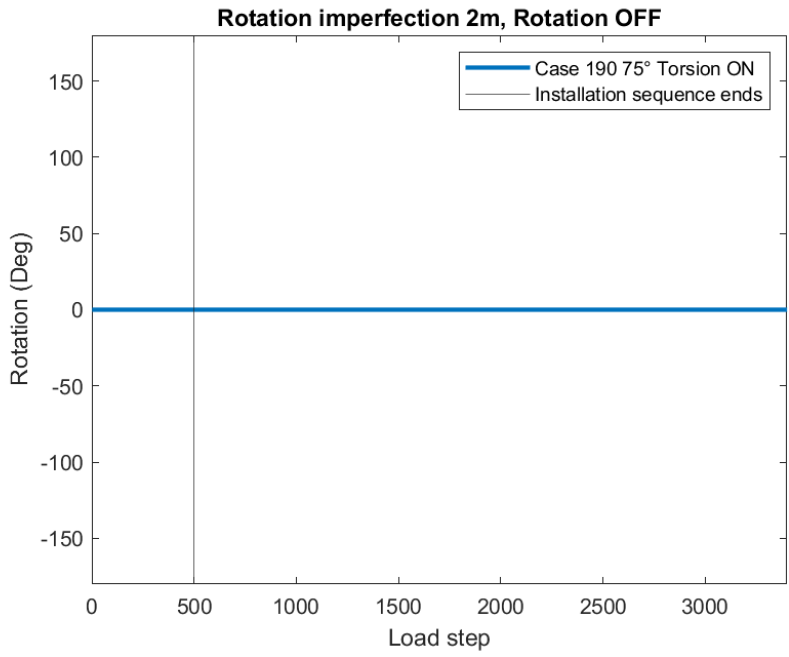


Figure 136: Rotation Case 190

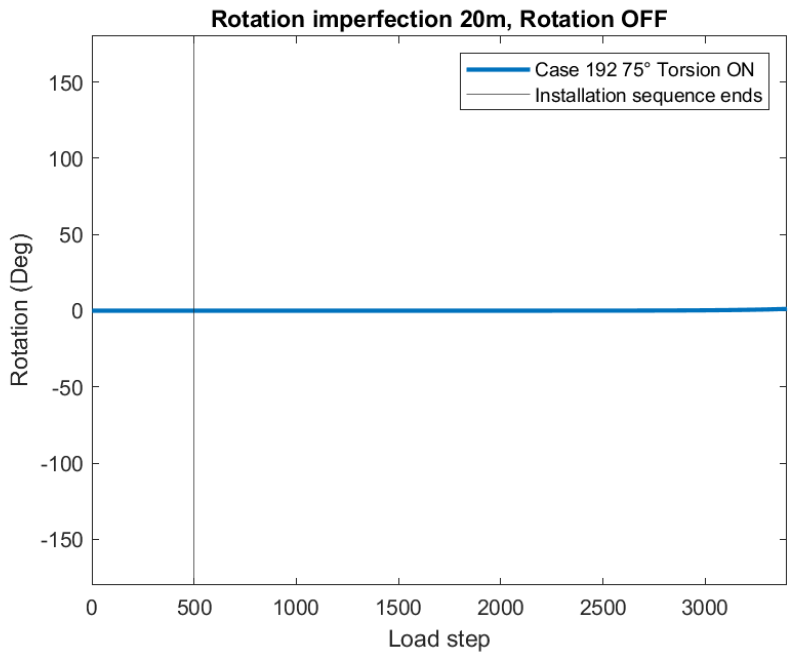


Figure 137: Rotation Case 192

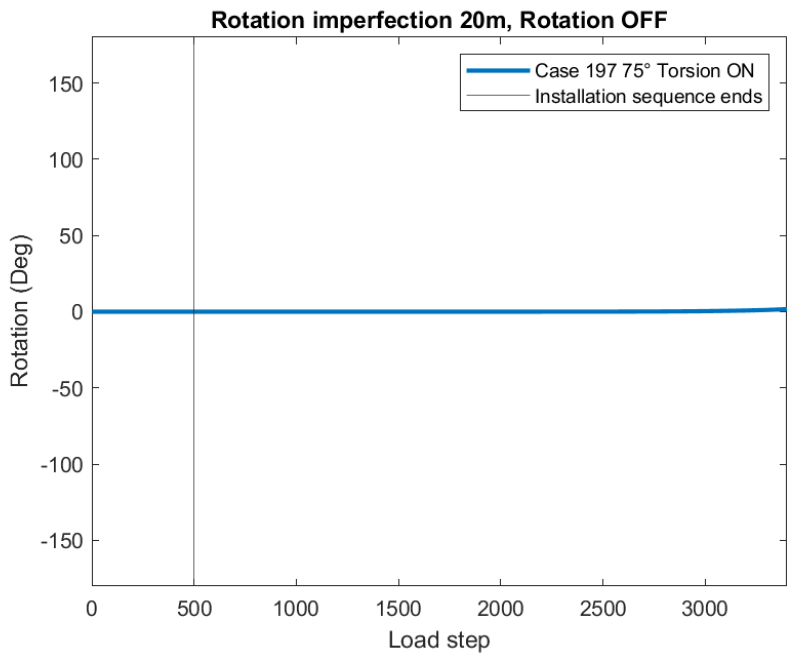


Figure 138: Rotation Case 197

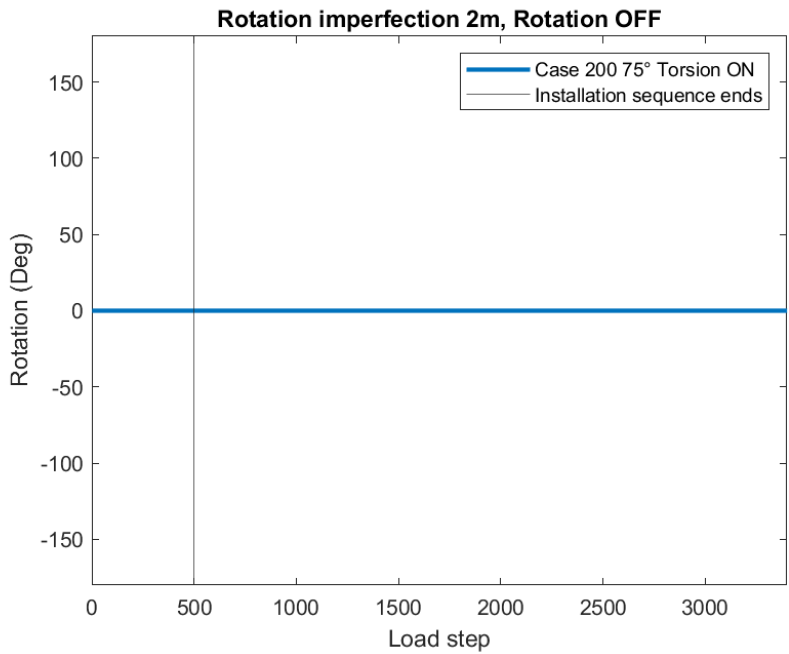


Figure 139: Rotation Case 200

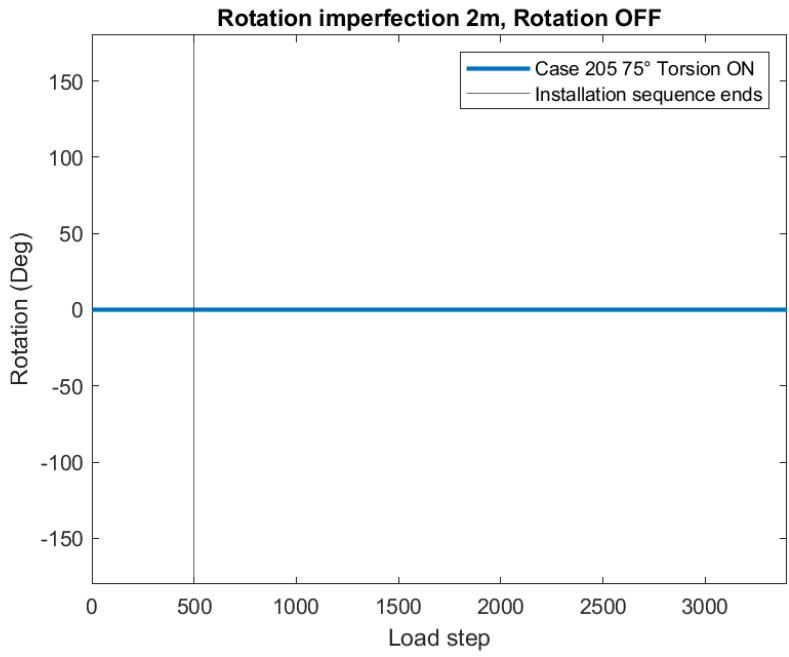


Figure 140: Rotation Case 205

C.3 Movement Vessel

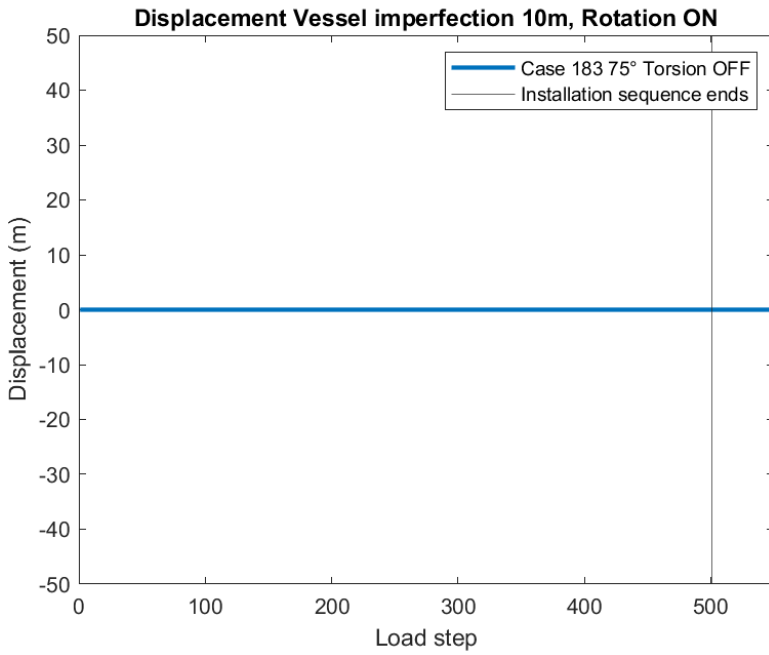


Figure 141: Displacement Vessel Case 183

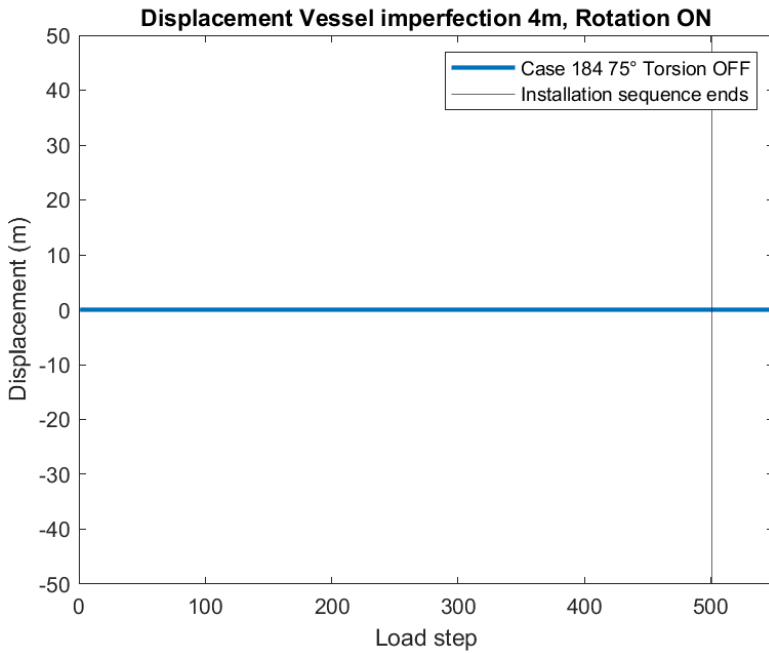


Figure 142: Displacement Vessel Case 184

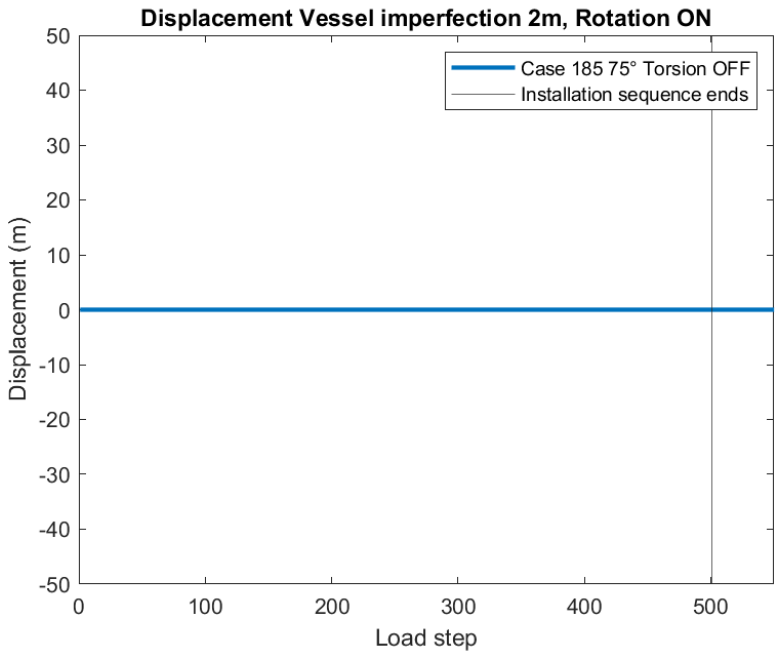


Figure 143: Displacement Vessel Case 185

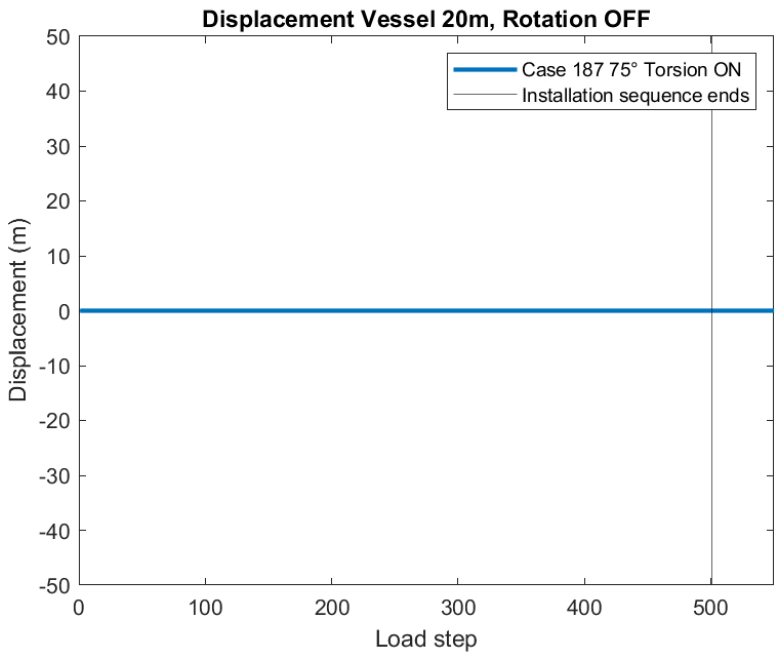


Figure 144: Displacement Vessel Case 187

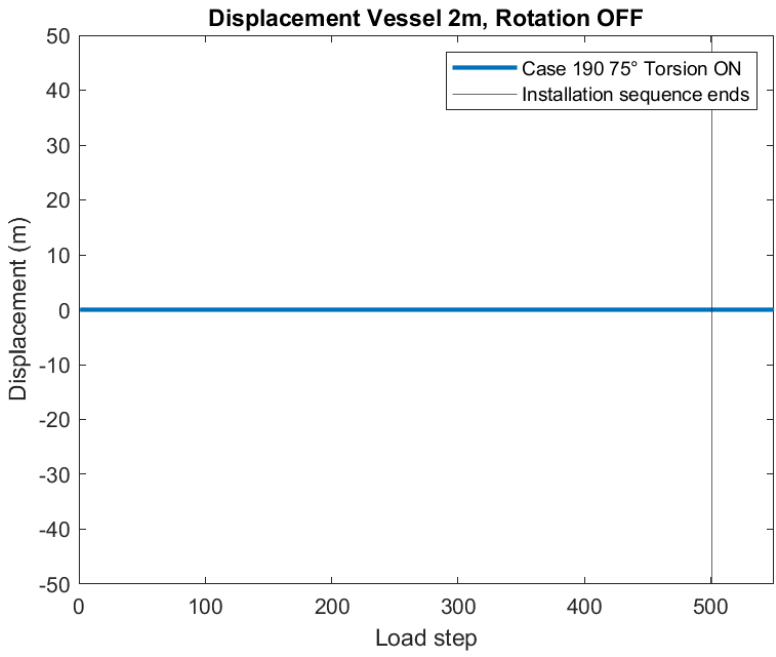


Figure 145: Displacement Vessel Case 190

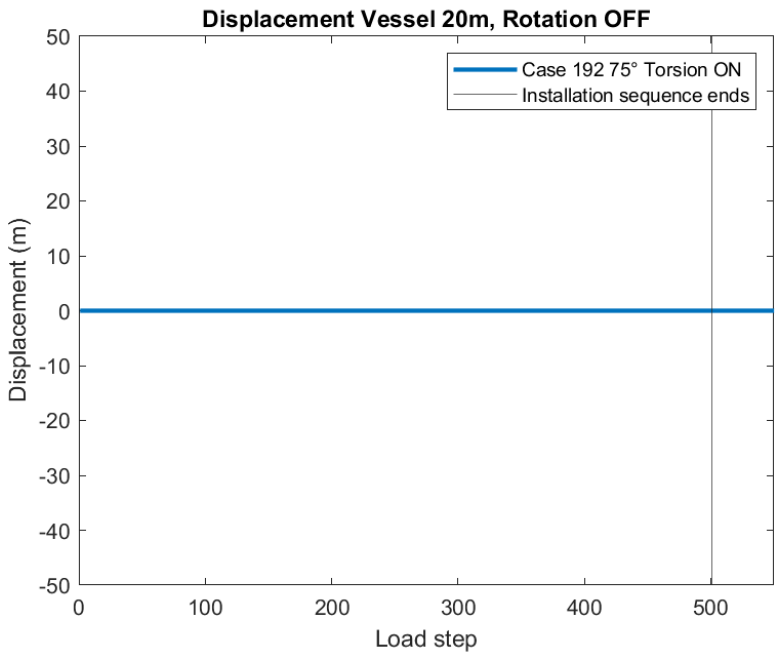


Figure 146: Displacement Vessel Case 192

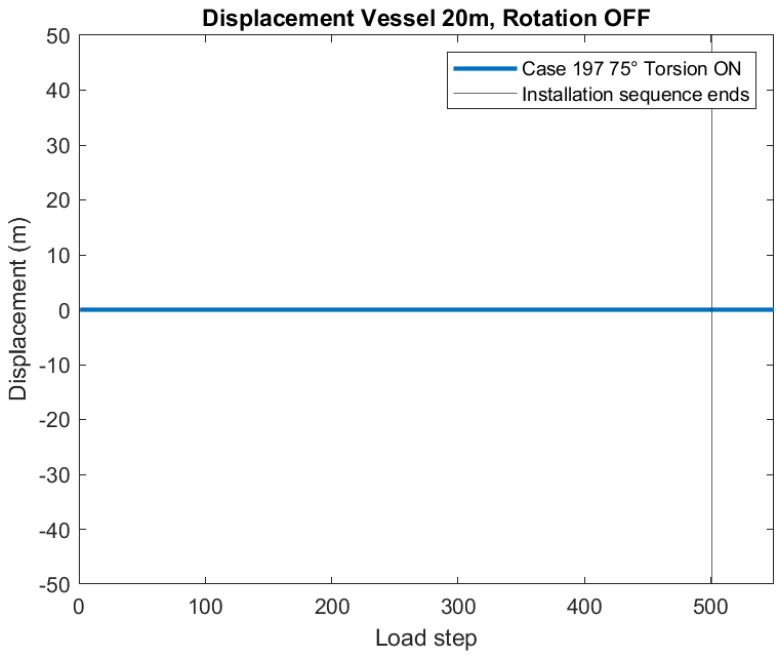


Figure 147: Displacement Vessel Case 197

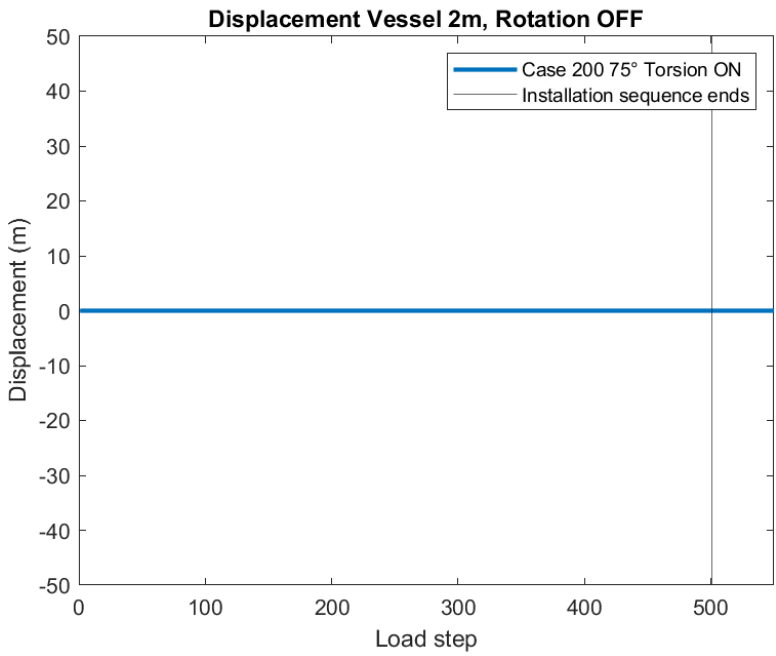


Figure 148: Displacement Vessel Case 200

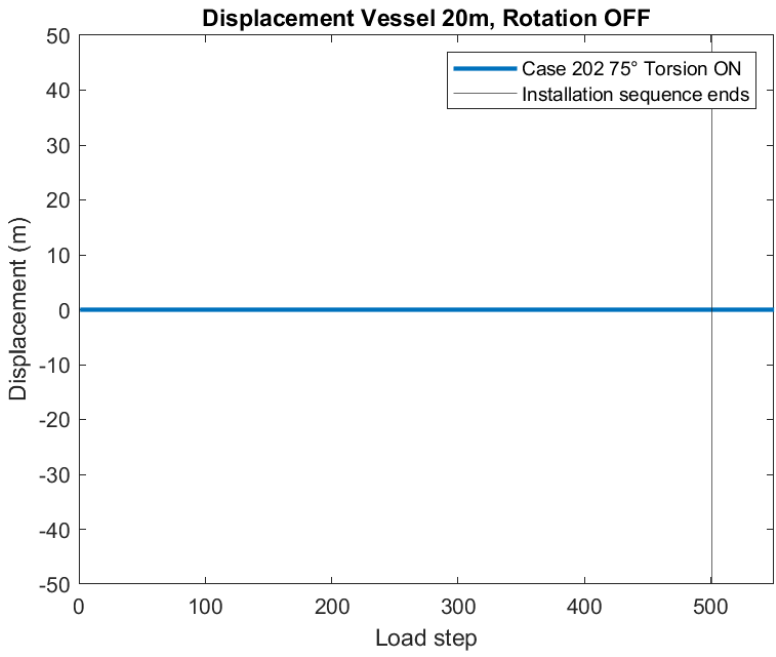


Figure 149: Displacement Vessel Case 202

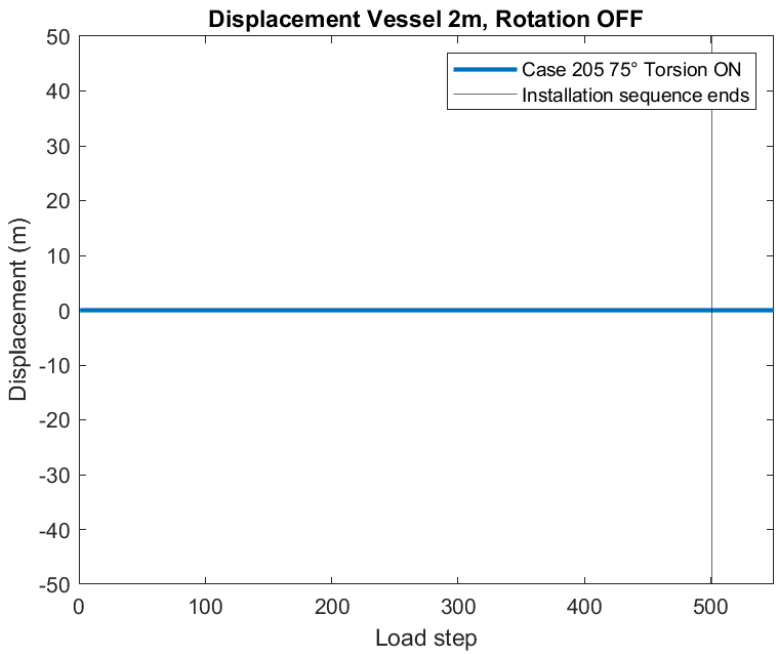


Figure 150: Displacement Vessel Case 205

D Input Files

D.1 SIMLA01

HEAD 16" Flowline – Static J-Lay – #angle departure angle

```
#
# Control data:
#
#          maxit  ndim  isolvr  npoint  ipri  conr  gacc  iproc
CONTROL  5000    3     1       8       1  1e-05  9.81  autostart
#          ielpip  ie2pip  incpip  nrolls  icaten  ivsnod
#          1       1000   1       0       1       1001
#
#  tens0    depang          freeb  rampan  rample  stirad  KP_tdp
#  0.0      #depang          31.27  0       0       0.0    3000.0
#
#          seabedgrp  stingergrp  vesselgrp  ivscog
#          seabed     none          vessel1    5001
# Defining visualization parameters:
#
# Visual presentation in X-POST:
VISRES INTEGRATION 1 sigma-xx
#
# Units used (for correct display in plots)
#
# This analysis is done in Mg, m, s
#          mass  length  time
UNITS  1.0e-3  1.0     1.0
#
# Analysis time control:
#
# First a step is done using the Autostart routine
#(defined in the Control card), afterwards load steps defined
#by the SIMLA card is carried out. The accuracy for the second
#load step sequence is also defined here.
#  t  dt  dtvi  dtdy  dt0  type  hla?
#          t    dt  dtvi  dtdy  dt0  type          hla?
TIMECO  1.0  1.  1.0  1.0  10.0  STATIC          NOHLA  AUTO  NONE  ALL  500  0  1.0e-4
TIMECO  20.0  1.0  19.0  1.0  10.0  STATIC-SIMLA  NOHLA  AUTO  NONE  ALL  500  5  1e-5
TIMECO  30.0  1.0  10.0  1.0  11.0  STATIC-SIMLA  NOHLA  AUTO  NONE  ALL  500  5  1e-5
#
# Building up model:
#
# Node input:
#          no          x          y          z
# pipe nodes.
NOCOOR  COORDINATES  1  -987.07  0.0  15.27
#          1001  2012.93  0.0  15.27
# vessel nodes.
NOCOOR  COORDINATES  5001  2012.93  0.0  0.0
#          5002  2025.86  0.0  0.0
#
# Sea nodes.
NOCOOR  COORDINATES  2101  150.0  -150.0  0.0
#          2102  -150.0  -150.0  0.0
#          2103  -150.0  150.0  0.0
#          2104  150.0  150.0  0.0
#
# Element connectivity input:
# Building up the connectivity matrix.
#          group  elty          material  no  n1  n2
ELCON  pipe1  pipe31  pipemat  1  1  2
```

```

#      n      nelinc nodinc
REPEAT 1000 1      1
#      group  elty      material no  n1  n2
ELCON  vessel1 pipe31  vessel1 5001 5001 5002
#      group  elty      material no  n1  n2  n3  n4
ELCON  seabed  cont125  routel 3001 1
#      n      nelinc nodinc
REPEAT 1000 1 1
#      group  elty      material no  n1  n2  n3  n4
ELCON  mwlse  seal150  seal 12101 2101 2102 2103 2104
#
# Orient input:
# Giving element normals
# pipe
#
#          no          x          y          z
ELORIENT COORDINATES      1      -987.07      1.0      15.27
#          1000      2012.93      1.0      15.27
#
# vessel
ELORIENT COORDINATES 5001      2000.0      1.0      0.0
#
ELORIENT EULERANGLES 3001      0      0      0
REPEAT 1000 1 0 0 0
#
# Element property input:
#
#name type rad th CDr Cdt CMr CMt wd ws ODp ODw rks
ELPROP pipe1 pipe 0.1918 0.022 1.0 0.1 2.0 1.0 0.321 0.073 0.5552 0.5552 0.5
# Vessel is defined as a very stiff but light beam.
ELPROP vessel1 pipe 1.0 0.1 0.8 0.1 2.0 0.2 41.4E-6 15.6E-6 0.1783 0.1783 0.5
#
# Defining the bottom properties:
#
# Cosurfpr data (contact surface properties):
#      name      data file      nlines KPl      x0      y0      fi      soil id
COSURFPR routel "Flowline.txt"      1      0.0      0.0 0.0 0.0 100
# Soil descriptions
#
#      id      startkp      stopkp      soil
COSUPR 100      0      9000      soil_1
#
# Contint data (contact interfaces):
#      groupn      mname      sname      isl      isn      istx      isty      istz      gt1
gt2
CONTINT seabed      pipe1      routel      1      800 10000 0.0 0.0 1000 #gt2
CONTINT mwlse      mwlse      pipe1
# Defining the properties of pipe and vessel:
#
#Loads:
#
# Curload input:
#      no      loc/glob      depth      curr      fi
CURLOAD 100      global      0      1.4      0.046
#          -20      1.4      0.046
#          -60      1.3      0.046
#          -250      1.1      0.046
#          -400      1.1      0.046
#          -700      0.85      0.046
#          -850      0.6      0.046
#          -1000      0.0      0.046
#
# Seaload specification:
#      name      x1      y1      x2      y2      icur ihist
SEALO mwlse -100000 -100000 100000 100000 100 400

```

```

#
# External pressure & gravity load
#   phi ghi
PELOAD 100 100
#
# History data:
#   no   istp  fac
# ext  press & grav:
THIST 100   0.0  0.00
          1.0  0.90
          1.1  1.00
          100.0 1.00

#
THIST 200   0.0  1.00
          100.0 1.00

#
THIST 300   0.0  0.00
          100.0 0.00

#
THIST 400   0.0  0.00
          100.0 0.00
#
# Constraint input:
#
# Pipe bottom end:
#
#           node  dof   ampl   thist
CONSTR PDISP GLOBAL    1    1    0.0    200
CONSTR PDISP GLOBAL    1    2    0.0    200
CONSTR PDISP GLOBAL    1    3    0.0    200
#
# Pipe upper-end connected to vessel node:
#
#           node  dof   C0  node   dof  C1
CONSTR CONEQ GLOBAL  1001  1    0   5002  1   1
CONSTR CONEQ GLOBAL  1001  2    0   5002  2   1
CONSTR CONEQ GLOBAL  1001  3    0   5002  3   1
#CONSTR CONEQ GLOBAL  1001  4    0   5002  4   1
CONSTR CONEQ GLOBAL  1001  5    0   5002  5   1
CONSTR CONEQ GLOBAL  1001  6    0   5002  6   1
#
# Vessel COG:
#
#           node  dof   ampl   thist
CONSTR PDISP GLOBAL  5001  1    0.0    200
CONSTR PDISP GLOBAL  5001  2    0.0    200
CONSTR PDISP GLOBAL  5001  3    0.0    200
CONSTR PDISP GLOBAL  5001  4    0.0    200
CONSTR PDISP GLOBAL  5001  5    0.0    200
CONSTR PDISP GLOBAL  5001  6    0.0    200
#
# Boundary condition data:
#
# Sea surface:
BONCON GLOBAL 2101  1
REPEAT 4 1
BONCON GLOBAL 2101  2
REPEAT 4 1
BONCON GLOBAL 2101  3
REPEAT 4 1
#
# Lay simulation data:
#
#   VesselID  npipe  ID_pipe  ID_sbd
SIMLA 5001    1    pipe1    seabed
#   file
"supp-lay-static.txt"    5

```

```

#      Sigf      Util  Type      nelst  TowerL  dist  tol
#      448000    1.0   T        2      24.0    0.0  0.5
#-----
# Joint property input:
#-----
JOINTPR_APPLY route1 pipe1
#      Type
JOINTPR_DEFINE route1 pipe
#
#KP1    KP2      rad    th    CDr    Cdt  CMr  CMt  wd    ws  ODp    ODw    rks  label
0.0    9000.0    0.1918  0.022  1.0   0.1  2.0  1.0  0.321  0.073  0.5552  0.5552  0.5  "FBE/PP"
#-----
# Material data
#-----
# Pipe:
#name    type    poiss  talfa    tecond  heatc  beta  ea    eiy    eiz    git
em      gm
MATERIAL pipemat linear  0.3  1.17e-5  50  800    0  6.27e6  1.14e5  1.1e5  8.6e4  210e6  79.3e6
#-----
MATERIAL vessel1 linear  0.3  1.17e-5  50  800  0  1.0e10  3.0e10  3.0e10  1.0e10  210e6  80.8e6
#-----
# Soil:
MATERIAL soil_1  contact  0.2    0.5    soilx  soily  soilz
#
MATERIAL soilx  epcurve  1      0.000    0.0
                0.005    1.0
                100.000  10.0
#
MATERIAL soily  epcurve  1      0.00    0.0
                0.10    1.0
                100.00    10.0
#
MATERIAL soilz  hycurve    -10000.0  -400000.0
                10000.0  400000.0
#-----
# Sea:
MATERIAL sea1    sea      1026e-3

```

D.2 SIMLA02

HEAD Static feed J-Lay – #angle departure angle, Skuld project

```
#
# Control data:
#
#          maxit  ndim  isolvr  npoint  ipri  conr  gacc  istres
CONTROL   500    3     1     8     1   1e-4  9.81  timeinit
#
#   file                time  pipegrp  vesselgrp  seagrps  stgrp  tcgrp
#   "simla_01"          30    pipel    vessell    mwlse    guidel  none
#
# Defining visualization parameters:
#
# Visual presentation in X-POST:
VISRES INTEGRATION 1 sigma-xx
VISRES INTEGRATION 1 strain-xx
#
# Units used (for correct display in plots)
#
# This analysis is done in Mg, m, s
#   mass  length  time
UNITS   1.0e-3  1.0   1.0
#
#
# Analysis time control:
#
#
# First a step is done using the Autostart routine
#(defined in the Control
# card), afterwards load steps defined by the SIMLA card
#is carried out.
# The accuracy for the second load step sequence is also defined here.
#           t    dt    dtvi  dtdy  dt0  type  hla?
TIMECO 1.0  1.0  1.0  1.0  2.0  STATIC  NOHLA
TIMECO 501.0  1.0  10.0  1.0  10.0  STATIC-FEED  NOHLA  AUTO GO-ON  ALL  100  5  1e-5
#
#
# Building up model:
#
# Node input:
#           no           x           y           z
#
# pipe nodes.
NOCOOR COORDINATES 1 -1000.0 0.0 14.30
          1001 2000.0 0.0 14.30
#
# Feed pipes
NOCOOR COORDINATES 15001 2000.0 0.0 14.30
          16500 2000.0 0.0 14.30
NOCOOR COORDINATES 25001 2003.0 0.0 14.30
          26500 2003.0 0.0 14.30
#
# Guide element
NOCOOR COORDINATES 6011 2003.0 0.0 14.30
NOCOOR COORDINATES 6012 2005.0 0.0 14.30
#
# vessel
NOCOOR COORDINATES 7001 2000.0 0.0 0.0
NOCOOR COORDINATES 7002 2005.0 0.0 0.0
#
# Sea:
```

```

NOCOOR COORDINATES  2101    150.0   -150.0    0.0
                    2102   -150.0   -150.0    0.0
                    2103   -150.0    150.0    0.0
                    2104    150.0    150.0    0.0
#
# Element connectivity input:
# Building up the connectivity matrix.
# Pipe group from static SIMLA analysis
#   group      elty      material  no  n1  n2  n3  n4
ELCON  pipe1      pipe31  pipemat  1  1  2
#       n       j
REPEAT 1000 1 1
#
# Pipe joints to be fed out:
#   group      elty      material  no  n1  n2
ELCON  pipe2      pipe31  pipemat 1001 15001 25001
#       n       j
REPEAT 1500 1 1
#
# Pipe guide:
#   group      elty      material  no  n1  n2
ELCON  guidel     pipe31  vessell 6011 6011 6012
#
# Vessel:
#   group      elty      material  no  n1  n2
ELCON  vessell   pipe31  vessell 7001 7001 7002
#
# Seabed for pipe from static SIMLA group
#   group      elty      material  no  n1
ELCON  seabed1  cont126  routel  3001 1
#       n       j
REPEAT 1000 1 1
#
# Seabed for feed pipe
#   group      elty      material  no  n1
ELCON  seabed2  cont126  routel  4001 15001
#       n       j
REPEAT 1500 1 1
#
# Sea
#   group      elty      material  no  n1  n2  n3  n4
ELCON  mwlse    sea150    seal    12101 2101 2102 2103 2104
#
# Orient input:
# Giving element normals
# pipe
#       no      x      y      z
ELORIENT COORDINATES  1000  -1000.0  1.0  14.30
                    1000  2000.0  1.0  14.30
# Feed pipe
#       no      x      y      z
ELORIENT COORDINATES 1001  2000.0  1.0  14.30
                    2500  2000.0  1.0  14.30
# Guide
#       no      x      y      z
ELORIENT COORDINATES 6011  2003.0  1.0  14.30
# Vessel
#       no      x      y      z
ELORIENT COORDINATES 7001  2005.0  1.0  0.0
# Seabed for original pipe
#       no      x      y      z
ELORIENT EULERANGLES 3001  0  0  0
REPEAT 1000 1 0 0 0
# Seabed for feed pipe

```

```

#
# node dof C0 m1 dof C1
CONSTR CONEQ LOCAL 1001 1 0.0 15001 1 1.0
CONSTR CONEQ LOCAL 1001 2 0.0 15001 2 1.0
CONSTR CONEQ LOCAL 1001 3 0.0 15001 3 1.0
CONSTR CONEQ LOCAL 1001 4 0.0 15001 4 1.0
CONSTR CONEQ LOCAL 1001 5 0.0 15001 5 1.0
CONSTR CONEQ LOCAL 1001 6 0.0 15001 6 1.0
#
# FEED pipe upper end:
# node dof C0 m1 dof C1
CONSTR CONEQ LOCAL 26500 1 0.0 6011 1 1.0
CONSTR CONEQ LOCAL 26500 2 0.0 6011 2 1.0
CONSTR CONEQ LOCAL 26500 3 0.0 6011 3 1.0
CONSTR CONEQ LOCAL 26500 4 0.0 6011 4 1.0
CONSTR CONEQ LOCAL 26500 5 0.0 6011 5 1.0
CONSTR CONEQ LOCAL 26500 6 0.0 6011 6 1.0
#
# FEED-group
# slave m1 m2 mf
CONSTR FEEDCONEQ 25001 6011 15002 6011
# NN ISLINC IMAINC
REPEAT 1499 1 1
#
# Boundary condition data:
#
# Sea surface:
BONCON GLOBAL 2101 1
REPEAT 4 1
BONCON GLOBAL 2101 2
REPEAT 4 1
BONCON GLOBAL 2101 3
REPEAT 4 1
#
# Curload input:
# no loc/glob depth curr fi
CURLOAD 100 global 0 1.4 0.046
-20 1.4 0.046
-60 1.3 0.046
-250 1.1 0.046
-400 1.1 0.046
-700 0.85 0.046
-850 0.6 0.046
-1000 0.0 0.046
#
# Seaload specification:
# name x1 y1 x2 y2 icur ihist
SEALO mwlse -100000 -100000 100000 100000 100 400
#
# WAVELO ELGRP REGULAR WAVENO WAVEHIST X0 Y0 ANG T H D PHI
WAVELO mwlse regular 100 400 0 0 0 10 0 380 0
#
# External pressure & gravity load
# phi ghi
PELOAD 100 110
#
# Lay simulation data:
# VesselID npipe ID_pipe ID_sbd
SIMLA 7002 2 pipe1 seabed1
pipe2 seabed2
# file nodes
"supp-lay-static.txt" 5
# Sigf Util Type nelst TowerL dist tol
448000 1.0 T 1 24.0 0.0 0.5
#

```

```

# Feed command:
# Giving simla the message to feed out elements in the analysis
#      group      T0      FIOP      rad/m      rad/kNm
FEED      pipe2      1.0      1      0.0      0.0
#-----
# Joint property input:
#-----
JOINTPR_APPLY route1 pipe1
#
#      Type
JOINTPR_DEFINE route1 pipe
# KPI KP2 rad th CDr Cdt CMr CMt wd ws ODp ODw rks label
0 900000 0.1918 0.022 1.0 0.1 2.0 1.0 0.321 0.073 0.5552 0.5552 0.5 "FBE/PP"
# Inistr input
#
INISTR 4002 5 #elid1 0.015 #elid2 0.015
#
# Inistr
THIST 4002 0.0 0.0
          7.0 0.0
          8.0 1.0
#-----
# History data:
#      no      istp      fac
# ext press & grav:
THIST 100 0.0 1.00
          100.0 1.00
#Dry mass
THIST 110 0.0 1.00
          501.0 1.00
          502.0 1.1
# Vessel motion
THIST 200 0.0 0.00
          100.0 0.00
#
# Current
THIST 400 0.0 0.0
          100.0 0.0
# Pressure
THIST 500 0.0 0.0
          1.0 0.0
# Temperature
THIST 600 0.0 0.0
          1.0 0.0
#-----
# Material data
#-----
# Pipe from static simla j-lay:
#name type poiss talfa tecond heatc beta ea eiy eiz git em gm
MATERIAL pipemat linear 0.3 1.17e-5 50 800 0 6.27e6 1.14e5 1.14e5 8.62e4 210e6 79.3e6
#-----
# Vessel:
#
MATERIAL vessel1 linear 0.3 1.17e-5 50 800 0 1.034e10 3.0e10 3.0e10 1.0e10 210e6 80.8e6
#-----
# Feed pipe
#name type hardpar poiss dummy talfa tecond heatc eps sigma
MATERIAL pipemat2 elastoplastic 1.0 0.3 0.0 1.17e-5 0.0 0.0 0.0000 0.0
          0.0018 367.0e3
          0.0023 409.0e3
          0.0052 451.0e3
          0.0291 493.0e3

```

```

#
# Soil:
# Soil giving the properties for newly laid pipe
#MATERIAL MNAME R.CONTACT MUX MUY MUTX XNAME YNAME ZNAME
#IXNAME [PZ YZNAME XYCHOICE]
MATERIAL soil_1 r_contact 0.2 0.5 0.2 soilx soil2y soilz
soiltx 0.1 helpy
# Soil giving the properties for already laid pipe
#MATERIAL MNAME R.CONTACT MUX MUY MUTX XNAME YNAME ZNAME
#IXNAME [PZ YZNAME XYCHOICE]
MATERIAL soil_2 r_contact 0.2 0.5 0.2 soilx soil2y soilz
soiltx 0.1 helpy
#
# Soil properties in axial direction
#      mname      mtype      ihard      eps      sigma
MATERIAL soilx      epcurve 1      0.000      0.0
                                     0.01      1.0
                                     100.000     10.0
# Soil properties in lateral direction for newly laid pipe
#      mname      mtype      ihard      eps      sigma
MATERIAL soily      epcurve 1      0.0      0.0
                                     0.1      1.0
                                     1000.0     10.0
# Soil properties in lateral direction for already laid pipe
#      mname      mtype      ihard      eps      sigma
MATERIAL soil2y      epcurve 1      0.0      0.0
                                     0.1      1.0
                                     1000.0     10.0
# Soil properties in lateral direction for newly laid pipe
#      mname      mtype      ihard      eps      sigma
MATERIAL soiltx      epcurve 1      0.0      0.0
                                     #spring 1.0
                                     1000.0     10.0
#
# Soil properties in z direction
#      mname      mtype      ihard      eps      sigma
MATERIAL soilz      hycurve      -10000.0 -400000.0
                                     10000.0     400000.0
#      mname      mtype      ihard      eps      sigma
MATERIAL helpy      hycurve      -10000.0 0.0
                                     10000.0     0.0
#
# Sea:
MATERIAL sea1      sea      1026e-3

```

D.3 SIMLA03

HEAD operating J-Lay - #angle departure angle, Skuld project

```
#
# Control data:
#
#          maxit  ndim  isolvr  npoint  ipri  conr  gacc  istres  irstep
CONTROL   500    3     1      8      1    1e-4  9.81   restart  501
#          MSTAT ALPHA1 ALPHA2 ALPHA [BETA GAMMA]
DYNCONT   1     0.0   0.09  -0.05
#
# Defining visualization parameters:
#
# Visual presentation in X-POST:
VISRES INTEGRATION 1 sigma-xx
VISRES INTEGRATION 1 strain-xx
#
# Units used (for correct display in plots)
#
# This analysis is done in Mg, m, s
#      mass  length  time
UNITS   1.0e-3  1.0    1.0
#
# Analysis time control:
#
# First a step is done using the Autostart routine
#(defined in the Control
# card), afterwards load steps defined by the SIMLA card
#is carried out.
# The accuracy for the second load step sequence is also defined
#here.
#          t    dt    dtvi    dtdy    dt0  type          hla?
TIMECO   1.0  1.0  1.0  1.0  2.0  STATIC        NOHLA
TIMECO   501.0  1.0  10.0  1.0  10.0  STATIC-FEED   NOHLA  AUTO none  ALL  100  5  1e-5
TIMECO   502.0  0.01  1.0  1.0  2.0  STATIC        NOHLA  AUTO none  DISP 100  5  1e-5
TIMECO   510.0  0.01  1.0  1.0  2.0  DYNAMIC       NOHLA  AUTO none  ALL  50  5  1e-5
TIMECO   530.0  0.01  1.0  1.0  2.0  DYNAMIC       NOHLA  AUTO none  ALL  50  5  1e-5
#
# Building up model:
#
# Node input:
#          no          x          y          z
#
# pipe nodes.
NOCOOR  COORDINATES  1          -1000.0    0.0    14.30
          1001        2000.0    0.0    14.30
#
# Feed pipes
NOCOOR  COORDINATES  15001       2000.0    0.0    14.30
          16500       2000.0    0.0    14.30
NOCOOR  COORDINATES  25001       2003.0    0.0    14.30
          26500       2003.0    0.0    14.30
#
# Guide element
NOCOOR  COORDINATES  6011        2003.0    0.0    14.30
NOCOOR  COORDINATES  6012        2005.0    0.0    14.30
#
# vessel
NOCOOR  COORDINATES  7001        2000.0    0.0    0.0
NOCOOR  COORDINATES  7002        2005.0    0.0    0.0
#
# Sea:
NOCOOR  COORDINATES  2101        150.0    -150.0  0.0
          2102        -150.0    -150.0  0.0
```

```

                2103   -150.0   150.0   0.0
                2104    150.0   150.0   0.0
#
#
# Element connectivity input:
# Building up the connectivity matrix.
# Pipe group from static SIMLA analysis
#   group      elty      material  no   n1   n2   n3   n4
ELCON  pipe1    pipe31    pipemat  1   1   2
#       n       j
REPEAT 1000 1 1
#
# Pipe joints to be fed out:
#   group      elty      material  no   n1   n2
ELCON  pipe2    pipe31    pipemat 1001 15001 25001
#       n       j
REPEAT 1500 1 1
#
# Pipe guide:
#   group      elty      material  no   n1   n2
ELCON  guide1   pipe31    vessel1 6011 6011 6012
#
# Vessel:
#   group      elty      material  no   n1   n2
ELCON  vessel1 pipe31    vessel1 7001 7001 7002
#
# Seabed for pipe from static SIMLA group
#   group      elty      material  no   n1
ELCON  seabed1 cont126  route1  3001 1
#       n       j
REPEAT 1000 1 1
#
# Seabed for feed pipe
#   group      elty      material  no   n1
ELCON  seabed2 cont126  route1  4001 15001
#       n       j
REPEAT 1500 1 1
#
# Sea
#   group      elty      material  no   n1   n2   n3   n4
ELCON  mw1sea   sea150    sea1    12101 2101 2102 2103 2104
#
#
# Orient input:
# Giving element normals
# pipe
#       no       x       y       z
ELORIENT COORDINATES 1 -1000.0 1.0 14.30
                1000  2000.0 1.0 14.30
# Feed pipe
#       no       x       y       z
ELORIENT COORDINATES 1001 2000.0 1.0 14.30
                2500  2000.0 1.0 14.30
# Guide
#       no       x       y       z
ELORIENT COORDINATES 6011 2003.0 1.0 14.30
# Vessel
#       no       x       y       z
ELORIENT COORDINATES 7001 2005.0 1.0 0.0
# Seabed for original pipe
#       no       x       y       z
ELORIENT EULERANGLES 3001 0 0 0
REPEAT 1000 1 0 0 0
# Seabed for feed pipe

```

```

#
# Connection between SIMLA-pipe and FEED-pipe:
#
# node dof C0 m1 dof C1
CONSTR CONEQ LOCAL 1001 1 0.0 15001 1 1.0
CONSTR CONEQ LOCAL 1001 2 0.0 15001 2 1.0
CONSTR CONEQ LOCAL 1001 3 0.0 15001 3 1.0
CONSTR CONEQ LOCAL 1001 4 0.0 15001 4 1.0
CONSTR CONEQ LOCAL 1001 5 0.0 15001 5 1.0
CONSTR CONEQ LOCAL 1001 6 0.0 15001 6 1.0
#
# FEED pipe upper end:
#
CONSTR CONEQ LOCAL 15002 1 0.0 25001 1 1.0 REPEAT 300 1 1
CONSTR CONEQ LOCAL 15002 2 0.0 25001 2 1.0 REPEAT 300 1 1
CONSTR CONEQ LOCAL 15002 3 0.0 25001 3 1.0 REPEAT 300 1 1
CONSTR CONEQ LOCAL 15002 4 0.0 25001 4 1.0 REPEAT 300 1 1
CONSTR CONEQ LOCAL 15002 5 0.0 25001 5 1.0 REPEAT 300 1 1
CONSTR CONEQ LOCAL 15002 6 0.0 25001 6 1.0 REPEAT 300 1 1
#
# FEED-group
#
# slave m1 m2 mf
##CONSTR FEEDCONEQ 25301 6011 15302 6011
# NN ISLINC IMAINC
#REPEAT 1199 1 1
#
# Boundary condition data:
#
#BONCON TYPE NODID DOF [MASTERNODE XANG YANG ZANG][REPEAT N NODINC]
BONCON GLOBAL 6011 1 REPEAT 2 1
BONCON GLOBAL 6011 2 REPEAT 2 1
BONCON GLOBAL 6011 3 REPEAT 2 1
BONCON GLOBAL 6011 4 REPEAT 2 1
BONCON GLOBAL 6011 5 REPEAT 2 1
BONCON GLOBAL 6011 6 REPEAT 2 1
# Catenary
BONCON GLOBAL 15302 1 REPEAT 1199 1
BONCON GLOBAL 15302 2 REPEAT 1199 1
BONCON GLOBAL 15302 3 REPEAT 1199 1
BONCON GLOBAL 15302 4 REPEAT 1199 1
BONCON GLOBAL 15302 5 REPEAT 1199 1
BONCON GLOBAL 15302 6 REPEAT 1199 1
# Catenary
BONCON GLOBAL 25301 1 REPEAT 1200 1
BONCON GLOBAL 25301 2 REPEAT 1200 1
BONCON GLOBAL 25301 3 REPEAT 1200 1
BONCON GLOBAL 25301 4 REPEAT 1200 1
BONCON GLOBAL 25301 5 REPEAT 1200 1
BONCON GLOBAL 25301 6 REPEAT 1200 1
# Left side of the pipe
BONCON GLOBAL 1 1 REPEAT 734 1
BONCON GLOBAL 1 2 REPEAT 734 1
BONCON GLOBAL 1 3 REPEAT 734 1
BONCON GLOBAL 1 4 REPEAT 734 1
BONCON GLOBAL 1 5 REPEAT 734 1
BONCON GLOBAL 1 6 REPEAT 734 1
# Sea surface:
BONCON GLOBAL 2101 1
REPEAT 4 1
BONCON GLOBAL 2101 2
REPEAT 4 1
BONCON GLOBAL 2101 3
REPEAT 4 1
#
# Curload input:

```

```

#          no      loc/glob      depth  curr      fi
CURLOAD 100 global
          -20      1.4      0.046
          -60      1.3      0.046
          -250     1.1      0.046
          -400     1.1      0.046
          -700     0.85     0.046
          -850     0.6      0.046
          -1000    0.0      0.046
#-----
# Seaload specification:
#      name      x1      y1      x2      y2      icur ihist
SEALO  mwlsa    -100000 -100000 100000 100000 100 400
#-----
# WAVELO ELGRP  REGULAR WAVENO  WAVEHIST X0 Y0 ANG T H  D  PHI
WAVELO  mwlsa  regular 100 400 0 0 0 10 0 380 0
#-----
# External pressure & gravity load
#      phi ghi
PELOAD 100 110
#-----
# Feed command:
# Giving simla the message to feed out elements in the analysis
#      group      T0      FIOP      rad/m      rad/kNm
#FEED  pipe2      1.0 1      0.0      0.0
#-----
# Joint property input:
#-----
JOINTPR_APPLY route1 pipe1
#
#      Type
JOINTPR_DEFINE route1 pipe
#KP1 KP2 rad th CDr Cdt CMr CMt wd ws ODp ODw rks label
0 900000 0.1918 0.022 1.0 0.1 2.0 1.0 0.321 0.073 0.5552 0.5552 0.5 "FBE/PP"
# Inistr input
#
INISTR 4002 5 #elid1 0.015 #elid2 0.015
#
# Inistr
THIST 4002 0.0 0.0
          7.0 0.0
          8.0 1.0
#-----
# History data:
#      no      istp fac
# ext press & grav:
THIST 100 0.0 1.00
          100.0 1.00
#Dry mass
THIST 110 0.0 1.00
          501.0 1.00
          502.0 1.1
# Vessel motion
THIST 200 0.0 0.00
          100.0 0.00
# Current
THIST 400 0.0 0.0
          100.0 0.0
# Pressure
THIST 500 0.0 0.0
          501.0 0.0
          510.0 20.0
# Temperature
THIST 600 0.0 0.0

```

```

510.0 0.0
530.0 100.0
#PILOAD HIST ELNR1 P1 [ELNR2 P2]
  PILOAD 500 1 1e3 2500 1e3
#PILOAD HIST ELNR1 P1 [ELNR2 P2]
  TLOAD 600 1 1 2500 1
#
# Material data
#
# Pipe from static simla j-lay:
# name type poiss talfa tecond heatc beta ea eiy eiz git em gm
MATERIAL pipemat linear 0.3 1.17e-5 50 800 0 6.27e6 1.14e5 1.14e5 8.62e4 210e6 79.3e6
#
# Vessel:
#
MATERIAL vessel1 linear 0.3 1.17e-5 50 800 0
1.034e10 3.0e10 3.0e10 1.0e10 210e6 80.8e6
#
# Feed pipe
# name type hardpar poiss dummy talfa tecond heatc eps sigma
MATERIAL pipemat2 elastoplastic 1.0 0.3 0.0 1.17e-5 0.0 0.0 0.0000 0.0
0.0018 367.0e3
0.0023 409.0e3
0.0052 451.0e3
0.0291 493.0e3
0.2000 535.0e3
#
# Soil:
# Soil giving the properties for newly laid pipe
#MATERIAL MNAME R.CONTACT MUX MUY MUTX XNAME YNAME ZNAME TXNAME [PZ YZNAME XYCHOICE]
MATERIAL soil_1 r_contact 0.2 0.5 0.2 soilx soil2y soilz soiltx 0.1 helpy
# Soil giving the properties for already laid pipe
#MATERIAL MNAME R.CONTACT MUX MUY MUTX XNAME YNAME ZNAME TXNAME [PZ YZNAME XYCHOICE]
MATERIAL soil_2 r_contact 0.2 0.5 0.2 soilx soil2y soilz soiltx 0.1 helpy
#
# Soil properties in axial direction
# mname mtype ihard eps sigma
MATERIAL soilx epcurve 1 0.000 0.0
0.01 1.0
100.000 10.0
# Soil properties in lateral direction for newly laid pipe
# mname mtype ihard eps sigma
MATERIAL soily epcurve 1 0.0 0.0
0.1 1.0
1000.0 10.0
# Soil properties in lateral direction for already laid pipe
# mname mtype ihard eps sigma
MATERIAL soil2y epcurve 1 0.0 0.0
0.1 1.0
1000.0 10.0
# Soil properties in lateral direction for newly laid pipe
# mname mtype ihard eps sigma
MATERIAL soiltx epcurve 1 0.0 0.0
#spring 1.0
1000.0 10.0
#
# Soil properties in z direction
# mname mtype ihard eps sigma
MATERIAL soilz hycurve -10000.0 -400000.0
10000.0 400000.0
# mname mtype ihard eps sigma
MATERIAL helpy hycurve -10000.0 0.0
10000.0 0.0

```

Sea :

MATERIAL sea1 sea 1026e-3

D.4 SIMPOST03

```
#GLPLOT RAFPRE MPFPRE XLEG XRES      YLEG YRES FELID LELID XSCL YSCL [ELEND INTPOI NLOADSTEP INC]
GLPLOT "simla_03" "Simla_03 Moment Y pipeline" "X" K-COR "Moment-Y KNm" ELMOM-Y 1 2500 1 1
#GLPLOT RAFPRE MPFPRE XLEG XRES      YLEG YRES FELID LELID XSCL YSCL [ELEND INTPOI NLOADSTEP INC]
GLPLOT "simla_03" "Simla_03 Moment Z pipeline" "X" K-COR "Moment-Z KNm" ELMOM-Z 1 2500 1 1
#GLPLOT RAFPRE MPFPRE XLEG XRES      YLEG YRES FELID LELID XSCL YSCL [ELEND INTPOI NLOADSTEP INC]
GLPLOT "simla_03" "Simla_03 Axial Force pipeline" "X" K-COR "Axial Force KN" ELFORCE-X 1 2500
1 1
#ELPLOT RAFPRE MPFPRE XLEG XRES YLEG YRES FELID LELID XSCL YSCL [ELEND ]
ELPLOT "simla_03" "Simla_03 Axial Force Temperature Pipeline"
"Temperature(C)" HIST600 "Axial Force(KN)" ELFORCE-X #resmid #resmid 1 1 2
#NOPLOT RAFPRE MPFPRE XLEG XRES YLEG YRES FNODID LNODID XSCL YSCL
#NOPLOT "simla_03" "Simla_03 Rotation imperfection" "Load Step" "LOADSTEP"
"Rotation about X" "NOROT-X" #rotmid #rotmid 1 1
#NOPLOT RAFPRE MPFPRE XLEG XRES      YLEG YRES FNODID LNODID XSCL YSCL
NOPLOT "simla_03" "Simla_03 Movement Vessel" "Load Step" "LOADSTEP"
"Movement Vessel (m)" "NODISP-Y"          7001 7001 1 1
```

D.5 Criteria Check MATLAB

```

clear all; close all; clc;

%Calculations local buckling
%Constants load condition
g = 9.81;
h = 380;
rhosw = 1026;
fo = 0.005;
ym = 1.15;
ysc = 1.04;
au = 0.96;
afab = 0.93;
yf = 1.2;
yc = 1.0;
SMYS = 4.48*10^8;
SMTS = 5.30*10^8;
pmin = 0;
fytemp = 30;
futemp = 30;
D = 0.5552;
t = 0.022;
v = 0.3;
E = 2.1*10^11;
pi = 20*10^6;

%Constants displacement condition
pmin1 = pi;
ye = 3.3;
pe = rhosw*g*h;
alphagw = 0.75;
alphah = 0.93;

%Calculations
fy = (SMYS-fytemp)*au;
fu = (SMTS - futemp)*au;
Pp = fy*afab*2*t/D;
Sp = fy*pi*(D-t)*t;
B = (60-D/t)/90;
ac = (1-B) + B *fu / fy;
Mp = fy*(D-t)^2*t;
fcb = fy/1.15;
pb = (2*t/(D-t))*fcb * 2/(3).^0.5;

if (pi-pe)/pb < 2/3
    ap = 1-B;
else
    ap = 1-3*b*((1-pi-pe)/pb);
end

%Calculating third degree polinomial to find pc
Pel = (2*E*(t/D)^3)/(1-v^2);
b = -Pel;
c = -(Pp^2+Pp*Pel*fo*D/t);
d = Pel*Pp^2;
u = 1/3*(-1/3*b^2+c);
Ve = 1/2*(2/27*b^3-1/3*b*c+d);
Phi = acos(-Ve/sqrt(-u^3));
y = -2*sqrt(-u)*cos(Phi/3+60*pi/180);
pc = y - 1/3 *b;
Ec = 0.78*((t/D)-0.01)*(1+5.75*(pmin1-pe)/pb)*alphah^-1.5*alphagw;
%%
num = '3';

```

```

% 5.28
% Gravity [Kg/ms^2]
% Water depth [m]
% Density Sea water [Kg/m^2]
% Ovality 5.14
% Table 5-2
% Table 5-3
% Table 5-4
% Table 5-5
% Table 4-4
% Table 4-5
% Pascal
% Pascal
% Empty inside
% Derating Figure 2 F101
% Derating Figure 2 F101
% Diameter [m]
% Thickness [m]
% Poisson
% Emodule [Pascal]
% Internal pressure [Pascal]

```

```

% 5.29
% Minimum internal pressure
% Table 5-10
% 4 B200
% Figure 2 D1000 Girth weld factor
% Table 7-5 Strain Hardening

```

```

%5.4
%5.5
%5.13
%5.20
%5.24
%5.22
%5.21
%5.9
%5.8

```

```

%5.12

```

```

%
%Find moments and axial force
elmomz=readMPF(['Simla_0',num,' Moment Z pipeline.mpf'])*1000;
elmomy=readMPF(['Simla_0',num,' Moment Y pipeline.mpf'])*1000;
elforce=readMPF(['Simla_0',num,' Axial Force pipeline.mpf'])*1000;
elforceci=readMPF(['Simla_0',num,' Axial Force Temperature Pipeline.mpf'])*1000;
elforcetemp=readMPFplot(['Simla_0',num,' Axial Force Temperature Pipeline.mpf']);
norot=readMPF(['Simla_0',num,' Rotation imperfection.mpf'])*180/3.14;
norottime=readMPFplot(['Simla_0',num,' Rotation imperfection.mpf']);
nodisp=readMPF(['Simla_0',num,' Movement Vessel.mpf']);
nodisptime=readMPFplot(['Simla_0',num,' Movement Vessel.mpf']);
%
% %Absolute value of moment z-direction going from KNm to Nm
elmomz_abs=abs(elmomz);
%
% %Absolute value of moment y-direction
elmomy_abs=abs(elmomy);
%
% %Absolute value of Axial force
elforce_abs=abs(elforce);
%
%
% %Calculating the design effective axial force
Ssd =elforce_abs*yf*yc;
%4.8
% %Calculating the resulting design moment
Msd = (((elmomz_abs.^2)+(elmomy_abs.^2)).^0.5)*yf*yc;
%4.6
% %Criterion check installation
crit1 = (ym*ysc*Msd/(ac*Mp)+((ym*ysc*Ssd)/(ac*Sp)).^2).^2 + (ym*ysc*(pe-pmin)/pc).^2;
% 5.28
crit2 = D/t;
crit3 = Ssd/Sp;
crit4 = (ym*ysc*Msd/(ac*Mp)+((ym*ysc*Ssd)/(ac*Sp)).^2).^2 + (ap*((pi-pe)/(ac*pb))).^2; % 5.19
if all(crit1 < 1)
    fprintf('Installation Load control condition OK %3.2f\n',max(max(crit1)))
else
    fprintf('Installation Load control condition NOT OK %3.2f\n',max(max(crit1)))
end
if crit2 < 15 && crit2 > 45
    fprintf('D/t is not in range, the criteria NOT OK%3.2f\n',max(max(crit2)))
else
    disp('D/t is fulfilled. OK')
end
if all(crit3 < 0.4)
    fprintf('Installation Total Axial force criteria is fulfilled. OK %3.2f\n',max(max(crit3)))
else
    fprintf('Higher than 0.4, the criteria NOT OK %3.2f\n',max(max(crit3)))
end
if all(crit4 < 1)
    fprintf('Operation Load control condition is fulfilled. OK %3.2f\n',max(max(crit4)))
else
    fprintf('Operation Load control condition is < 1, criteria NOT OK %3.2f\n',max(max(crit4)))
end

fileID = fopen('Results.txt','A');
fprintf(fileID,'\n%5f %5f %5f %5f\n',max(max(crit1)));
fprintf(fileID,'\n%5f %5f %5f %5f\n',max(max(crit4)));
fclose(fileID);

h = plot(elforcetemp,elforceci,'lineWidth',2);

title('Axial force imperfection #length ')

```

```

xlabel('Temperature (Celsius)')
ylabel('Axial Force (N)')
saveas(h,'Case#case.png')

r = plot(norottime , norot , 'lineWidth' , 2);
hold on
xline(501, '-')
legend('Case #case #deg Torsion #torsion', 'Installation sequence ends')
title('Rotation imperfection #length, Rotation #rotation')
xlabel('Load step')
xlim([0 3400])
ylabel('Rotation (Deg)')
ylim([-180 180])
saveas(r, 'RotationCase#case.png')
hold off

d = plot(nodisptime , nodisp , 'lineWidth' , 2);
hold on
xline(501, '-')
legend('Case #case #deg Torsion #torsion', 'Installation sequence ends')
title('Displacement Vessel #length, Rotation #rotation')
xlabel('Load step')
xlim([0 550])
ylabel('Displacement (m)')
ylim([-50 50])
saveas(d, 'DisplacementVesselCase#case.png')
hold off

```

D.6 Read MPF files

```
function out=readMPF(filename)
    FID = fopen(filename);
    assert(FID>0)
    ii=1;
    while ~ feof(FID)
        line = fgetl(FID);
        if line(1) == 'V'

            a=sscanf(line, 'VALUES %f %f ');
            out(1, ii)=a(2);
            jj=2;
            while ~ feof(FID)
                line = fgetl(FID);
                if line(1) ~= 'M'
                    a=sscanf(line, '%f %f ');
                    out(jj, ii)=a(2);
                    jj=jj+1;

                else
                    break
                end
            end
            ii=ii+1;
        end
    end
    fclose all;
end
```

D.7 Plot Combined Cases

```
num = '125';
num1 = '130';
num2 = '135';
num3 = '140';
num4 = '145';
num5 = '150';

DOF = 'ON';
Length = '2m';

%Find moments and axial force
%elforcei=readMPF(['Case',num,'.mpf'])*1000;
elforcetemp=readMPFplot(['Case',num,'.mpf']);

elforcei1=readMPF(['Case',num1,'.mpf'])*1000;
elforcetemp1=readMPFplot(['Case',num1,'.mpf']);

elforcei2=readMPF(['Case',num2,'.mpf'])*1000;
elforcetemp2=readMPFplot(['Case',num2,'.mpf']);

elforcei3=readMPF(['Case',num3,'.mpf'])*1000;
elforcetemp3=readMPFplot(['Case',num3,'.mpf']);

elforcei4=readMPF(['Case',num4,'.mpf'])*1000;
elforcetemp4=readMPFplot(['Case',num4,'.mpf']);

elforcei5=readMPF(['Case',num5,'.mpf'])*1000;
elforcetemp5=readMPFplot(['Case',num5,'.mpf']);

hold on
h = plot(elforcetemp,elforcei,'lineWidth',2,'DisplayName','Case ',num,' 70 Torsion ON');
h1 = plot(elforcetemp1,elforcei1,'lineWidth',2,'DisplayName','Case ',num1,' 75 Torsion ON');
h2 = plot(elforcetemp2,elforcei2,'lineWidth',2,'DisplayName','Case ',num2,' 80 Torsion ON');
h3 = plot(elforcetemp3,elforcei3,'lineWidth',2,'DisplayName',['Case ',num3,' 70 Torsion OFF']);
h4 = plot(elforcetemp4,elforcei4,'lineWidth',2,'DisplayName',['Case ',num4,' 75 Torsion OFF']);
h5 = plot(elforcetemp5,elforcei5,'lineWidth',2,'DisplayName',['Case ',num5,' 80 Torsion OFF']);

title(['Axial force imperfection ', Length, ', ', ' ', 'Rotation ', DOF,]);
xlabel('Temperature (Celsius)')
ylabel('Axial Force (N)')

lgd = legend;
lgd.NumColumns = 2;
saveas(h3,['Length_', '_Contact_',DOF,'.png'])
```

D.8 GITBASH script

```
rmdir Case_191_40m_75_R_contact_all_gt1
mkdir Case_191_40m_75_R_contact_all_gt1
mv Results.txt Case_191_40m_75_R_contact_all_gt1/Results.txt
cp Flowline.txt Case_191_40m_75_R_contact_all_gt1/Flowline.txt
cp template_01.sif Case_191_40m_75_R_contact_all_gt1/simla_01.sif
cp template_02.sif Case_191_40m_75_R_contact_all_gt1/simla_02.sif
cp template_03.sif Case_191_40m_75_R_contact_all_gt1/simla_03.sif
cp simpost_03.spi Case_191_40m_75_R_contact_all_gt1/simpost_03.spi
cp Criteria_check.m Case_191_40m_75_R_contact_all_gt1/Criteria_check.m
cp readMPF.m Case_191_40m_75_R_contact_all_gt1/readMPF.m
cp readMPFplot.m Case_191_40m_75_R_contact_all_gt1/readMPFplot.m

cd Case_191_40m_75_R_contact_all_gt1
#
sed -i '/#case/s//191/g' Criteria_check.m
sed -i '/#length/s//40m/g' Criteria_check.m
sed -i '/#rotmid/s//15010/g' simpost_03.spi
sed -i '/#depang/s//1.309/g' simla_01.sif
sed -i '/#angle/s//75/g' simla_01.sif
sed -i '/#CONSTR/s//CONSTR/g' simla_01.sif
sed -i '/#gt2/s//1/g' simla_01.sif
sed -i '/#deg/s//75/g' Criteria_check.m
sed -i '/#torsion/s//ON/g' Criteria_check.m
sed -i '/#rotation/s//OFF/g' Criteria_check.m

simla << eod
simla_01
eod
#
sed -i '/#CONSTR/s//CONSTR/g' simla_02.sif
sed -i '/#angle/s//75/g' simla_02.sif
sed -i '/#elid1/s//1001/g' simla_02.sif
sed -i '/#spring/s//1.2/g' simla_02.sif
sed -i '/#spring/s//1.2/g' simla_03.sif
sed -i '/#elid2/s//1020/g' simla_02.sif
sed -i '/#gt2/s//1/g' simla_02.sif
sed -i '/#CONSTR/s//CONSTR/g' simla_03.sif
sed -i '/#angle/s//75/g' simla_03.sif
sed -i '/#elid1/s//1001/g' simla_03.sif
sed -i '/#elid2/s//1020/g' simla_03.sif
sed -i '/#gt2/s//1/g' simla_03.sif
simla << eod
simla_02
eod
#
mv simla_02.raf simla_03.raf
simla << eod
simla_03
eod
#
sed -i '/#resmid/s//1010/g' simpost_03.spi
simlae << eod
simpost_03
eod
#
rm simla_01.raf
rm simla_03.raf
#
matlab -nodesktop -nosplash -wait -r "Criteria_check; exit;"
cp RotationCase191.png ..
cp Case191.png ..
cp Results.txt ..
```

```

cd ..
#
#
#NEW LENGHT
#
#
rmdir Case_192_20m_75_R_contact_all_gt1
mkdir Case_192_20m_75_R_contact_all_gt1
mv Results.txt Case_192_20m_75_R_contact_all_gt1/Results.txt
cp Flowline.txt Case_192_20m_75_R_contact_all_gt1/Flowline.txt
cp template_01.sif Case_192_20m_75_R_contact_all_gt1/simla_01.sif
cp template_02.sif Case_192_20m_75_R_contact_all_gt1/simla_02.sif
cp template_03.sif Case_192_20m_75_R_contact_all_gt1/simla_03.sif
cp simpost_03.spi Case_192_20m_75_R_contact_all_gt1/simpost_03.spi
cp Criteria_check.m Case_192_20m_75_R_contact_all_gt1/Criteria_check.m
cp readMPF.m Case_192_20m_75_R_contact_all_gt1/readMPF.m
cp readMPFplot.m Case_192_20m_75_R_contact_all_gt1/readMPFplot.m

cd Case_192_20m_75_R_contact_all_gt1
#
sed -i '/# case /s//192/g' Criteria_check.m
sed -i '/# length /s//20m/g' Criteria_check.m
sed -i '/# rotmid /s//15005/g' simpost_03.spi
sed -i '/# depang /s//1.309/g' simla_01.sif
sed -i '/# angle /s//75/g' simla_01.sif
sed -i '/# CONSTR /s//CONSTR/g' simla_01.sif
sed -i '/# gt2 /s//1/g' simla_01.sif
sed -i '/# deg /s//75/g' Criteria_check.m
sed -i '/# torsion /s//ON/g' Criteria_check.m
sed -i '/# rotation /s//OFF/g' Criteria_check.m

simla << eod
simla_01
eod
#
sed -i '/# CONSTR /s//CONSTR/g' simla_02.sif

sed -i '/# spring /s//1.2/g' simla_02.sif
sed -i '/# spring /s//1.2/g' simla_03.sif
sed -i '/# angle /s//75/g' simla_02.sif
sed -i '/# elid1 /s//1001/g' simla_02.sif
sed -i '/# elid2 /s//1010/g' simla_02.sif
sed -i '/# gt2 /s//1/g' simla_02.sif
sed -i '/# CONSTR /s//CONSTR/g' simla_03.sif
sed -i '/# angle /s//75/g' simla_03.sif
sed -i '/# elid1 /s//1001/g' simla_03.sif
sed -i '/# elid2 /s//1010/g' simla_03.sif
sed -i '/# gt2 /s//1/g' simla_03.sif
simla << eod
simla_02
eod
#
mv simla_02.raf simla_03.raf
simla << eod
simla_03
eod
#
sed -i '/# resmid /s//1005/g' simpost_03.spi
simlae << eod
simpost_03
eod
#
rm simla_01.raf
rm simla_03.raf

```

```
#
matlab -nodesktop -nosplash -wait -r "Criteria_check; exit;"
cp RotationCase192.png ..
cp Case192.png ..
cp Results.txt ..
cd ..
```

