University of Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/Specialization: **Offshore Technology / Marine and Subsea Technology**	Spring semester, 2019 Open / ~~Restricted~~ access
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Title of master's thesis: **Feasibility Study of Application of Residual Curvature Method in Deepwater Free Hanging Risers**	
Credits (ECTS): 30	
Keywords: Residual Curvature Method RCM, Steel Catenary Riser SCR, Weight Distributed Steel Catenary Riser WDSCR, Extreme Response Analysis, Fatigue Analysis, Deepwater, Gulf of Mexico GoM.	Pages: 128 + Appendix / Enclosure: 14 Stavanger, June 15, 2019 Date/year

Feasibility Study of Application of Residual Curvature Method in Deepwater Free Hanging Risers

Master Thesis

Marine and Offshore Technology: Subsea Technology

Jeison Leandro Vesga Hernández

Spring 2019

Abstract

The Offshore Oil and Gas industry has been moving to deeper water and needs to manage production in more extreme conditions. Risers systems are essential components for the transportation of these hydrocarbons from producing subsea wells to topside facilities. To reduce costs and improve safety, it is vital to use the most proper and effective design for these conductor pipes. This thesis proposes a riser configuration to cope with high floater motions in deep water under extreme conditions such as hurricanes, producing from a typical subsea well.

The idea was to modify the geometry of sections of free hanging steel catenary risers to improve its performance by partially decoupling the touch down point of this conductor pipe from floater motions. Residual Curvature Method (RCM) was applied to Steel Catenary Riser (SCR) to achieve this. This method has been applied to control thermal buckling during operation in subsea pipelines. The mentioned technique involves the creation of un-straightened segments or sections with residual curvature in the riser during installation. For ease, any SCR with sections with residual curvature applied will be named as RCSCR.

This project focuses on the Residual Curvature Method applied to a high-pressure line steel catenary riser for 1500m water depth. It was determined that the RCM is a self-limiting process, where the section with residual curvature is able to absorb compressive forces, improve utilization and fatigue in the touch down area of the riser; however, the un-straightened section itself brings more bending moment, utilization and fatigue where it is located, limiting its application. The most optimum configuration for the section, which is made up of 4 subsections, must be applied close to the touch down area and is limited to a curvature of 0.009 m^{-1} for a 10 inch-internal diameter and 39 mm of wall thickness SCR; with this, obtaining a residual strain of 0.15% in the section. Likewise, it was found that the un-straightened section length that perform best was 180 m which is 12% of the water depth.

A screening of the downward velocities at the hang-off point up in the platform was considered and analyzed, identifying the maximum values for buckling utilization, bending moment and compression, which are main critical responses. SCR with RCM, RCSCR was investigated in terms of the capabilities needed to handle the floater motions. The riser configuration was examined concerning strength, as well as fatigue performances to determine its limitations and merits.

The strength assessment was achieved by using load cases with different sea states, including a typical 3h-winter storm and a hurricane occurring in the Gulf of Mexico. In this study, the sea states were established following JONSWAP wave spectra. The screening approach was based on the downward velocity or heave velocity at the hang-off point, which has been validated to be the principal design criteria for riser integrity. All the checks were performed in accordance with DNV codes.

According to the results for extreme analysis, the SCR studied is restricted to a maximum downward velocity of 2.64 m/s, while the Steel Catenary Riser with Residual Curvature method (RCSCR) can cope with downward velocities up to 2.94 m/s at the hang-off point. Similarly, it was validated that the selected Weight Distributed SCR (WDSCR) configuration for this study can cope with a downward velocity of 3.2 m/s, while the combination of the Residual Curvature Method and WDSCR configuration can improve the coping of downward velocity at the hang-off point up to 4.01 m/s.

On the other hand, the fatigue analysis of the riser configurations was carried out taking into account wave-induced fatigue. In general, the application of the un-straightened section through the Residual Curvature Method extended the life in fatigue of the SCR, increasing its value from 243 years to 599 years in the RCSCR configuration.

The application of the Residual Curvature Method was found to be a viable solution to improve the performance for strength and fatigue of SCR and WDSCR configurations to cope with high motion of floaters. Investigation needs to be done for stability in riser-rotation while in operation, durability and optimization of the un-straightened section. This thesis work showed that, although deep water free hanging risers (SCR and WDSCR) can be limited for coping with large floater motions, economic and innovative solutions can be proven to increase their feasibility to handle higher heave motions in extreme conditions.

All in all, even though it is a self-limiting technique, the application of the Residual Curvature Method reduces stress and fatigue loads in SCR and WDSCR configurations.

Keywords: Residual Curvature Method RCM, Steel Catenary Riser SCR, Weight Distributed Steel Catenary Riser WDSCR, Extreme Response Analysis, Fatigue Analysis, Deepwater, Gulf of Mexico GoM, Hurricane Sea State condition.

Acknowledgement

This report fulfills the prerequisite to complete the Master of Science in Marine and Offshore Technology at the University of Stavanger. This project was carried out at Stavanger office of Subsea7 from February 2019 and was completed in the middle of June 2019.

First, I would like to give my sincere gratitude to Professor Daniel Karunakaran for giving me the opportunity to be his master thesis student. His energy, pragmatic knowledge, valuable corrections and comments have been important for the development of this thesis. It is certainly a great honor to have written my thesis in the company Subsea7 and with such outstanding Professor.

Secondly, I want to express my gratitude to Professor Ljiljana Djapic Oosterkamp from the University of Stavanger who introduced to this interesting research topic and allowed me to be a part of it in the course of Marine Operations. Likewise, my deep appreciation to Professor Dimitrios Pavlou, for his offering the student assistantship in the course of Advance Solid Mechanics.

Next, I would like to thank the Hydrodynamics and Ocean Technology group of Subsea7 Stavanger, for taking their time in helping me with my learning process and the use of the software OrcaFlex, especially to Doctor Adekunle Peter Orimolade for his valuable inputs, patience and knowledge sharing which helped me in writing the thesis.

Many thanks to the “Foundation for the Future of Colombia” Colfuturo, for its financial help and to the government of Norway for giving me the opportunity to come to the country to do this master's degree. Likewise, the admission committed of the University and the Department of Mechanical and Structural Engineering for giving me the opportunity to belong to this wonderful University.

From very deep in my heart, thanks to my beautiful family in Colombia; especially my mom Luz Esther and sister Jessica, and to my beloved Linda Evhans for supporting me from the distance in this life project. The love that I feel from all you are the engine that drives me to keep going.

Jeison Leandro Vesga Hernández
Stavanger, 15 June 2019

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List of abbreviations

ALS	Accidental Limit State
API	American Petroleum Institute
DDF	Deep Draft Floater
DFF	Design Fatigue Factor
DNV	Det Norske Veritas
DV	Max. Downward Velocity (Normally refers at Hang-off point)
DNV	Det Norske Veritas
FBE	Fusion Bonded Epoxy
FE	Finite Element
FLS	Fatigue Limit State
FPS	Floating Production System
FPSO	Floating Production Storage and Offloading
GOM	Gulf of Mexico
HRT	Hybrid Riser Tower
ID	Inner Diameter
JONSWAP	Joint Operation North Sea Wave Project
LC	Load Case
LRFD	Load and Resistance Factor Design
OD	Outer Diameter
PET	Pipeline Engineering Tool
RAO	Response Amplitude Operator
RC	Residual Curvature
RCS	Residual Curvature Strain
RCSCR	Steel Catenary Riser with Residual Curvature
RCL	Residual Curvature Length
RCM	Residual Curvature Method
RCSCR	Residual Curvature Applied to SCR
RS	Residual Strain
SCF	Stress Concentration Factor
SCR	Steel Catenary Riser

SLOR	Single Line Offset Riser
SLS	Serviceability Limit State
SLWR	Steel Lazy Wave Riser
TDZ	Touchdown Zone or Touchdown Area TDA
TDP	Touchdown Point
TLP	Tension Leg Platform
TTR	Top Tension Riser
UF	Utilization Factor
ULS	Ultimate Limit State
VIV	Vortex Induced Vibration
WSD	Working Stress Design
WD	Water Depth
WDSCR	Weight Distributed Steel Catenary Riser

Nomenclature

For Riser Theory:

A	Cross section area
C_D	Drag Coefficient
C_A	Added mass Coefficient
Cf	Design case Factor
D	Nominal Outside diameter
f_0	Initial Ovality
g	Acceleration of gravity
Hs	Significant Wave Height ($H_{1/3}$)
Mpa	Mega Pascal
pb	Burst resistance
pc	Resistance for external pressure for hoop buckling
pd	Design pressure
pe	External Pressure
pel	Elastic collapse pressure (instability) of a pipe
pi	Internal (local) pressure
pe	External (local) pressure
Re	Reynolds number
s	Seconds
t	time
tcorr	Internal and external corrosion allowance
Te	tons

For Residual Curvature Method:

s	Distance in the pipeline from the touch down point TDP [m]
ds	Arc length [m]
d	Water depth [m]
k_r	Residual Curvature [1/m]
ε_r	Residual Strain
L	Length of the suspended pipeline [m]
k(s)	Nominal curvature of the pipe [1/m]
E	Young modulus [N/m^2]
I	Second moment of inertia [m^4]
T	Top vessel tension [N]
T_h	Horizontal component of top tension [N]
T_v	Vertical component of the top tension [N]
H_t	Horizontal tension [N]
R	Radius of curvature [m]
k_{res}	Residual curvature [1/m]
L_{curve}	Residual curvature length [m]
t	Wall thickness of the pipe [m]
σ	Bending stress [Pa]

Chapter 1. Introduction

This chapter provides background, scope and purpose for this study project.

1.1 Background study for offshore development and riser systems

The year 2017 set record as low year for discoveries of conventional quantities of oil and gas globally. Lower than 7 billion barrels of oil equivalent were discovered. (Rystad Energy Research Analysis, 2018). According to the international Energy Agency (IEA), the use of primary and secondary oil as energy supply source has increased from 3.2 Million kilotons of oil equivalent (ktoe) in 1990 to 4.4 Million ktoe in 2016, and the primary energy supply needs will continue increasing at approximately 0.12 Million of ktoe per year. (International Energy Agency IEA, 2018). Adding to this, onshore and shallow offshore oil and gas sources are limited, therefore it is imperative to work in technologies to explore and produce in more remote areas in the sea and at deeper water.

Offshore industry started producing from wells tied back to fixed platforms back in the 1940's. So far, the deepwater development systems in the Gulf of Mexico (GoM) for example, comprises the following options: Bottom supported and vertically moored structures (Fixed Platform, Compliant Tower, Tension Leg Platforms) for shallow and medium range deep water, and floating production and subsea systems (Spar, floating production systems, floating production storage vessel) for deep waters as illustrated in Figure 1. (BBSE Bureau of Safety and Environmental Enforcement for Offshore Structures, 2018).

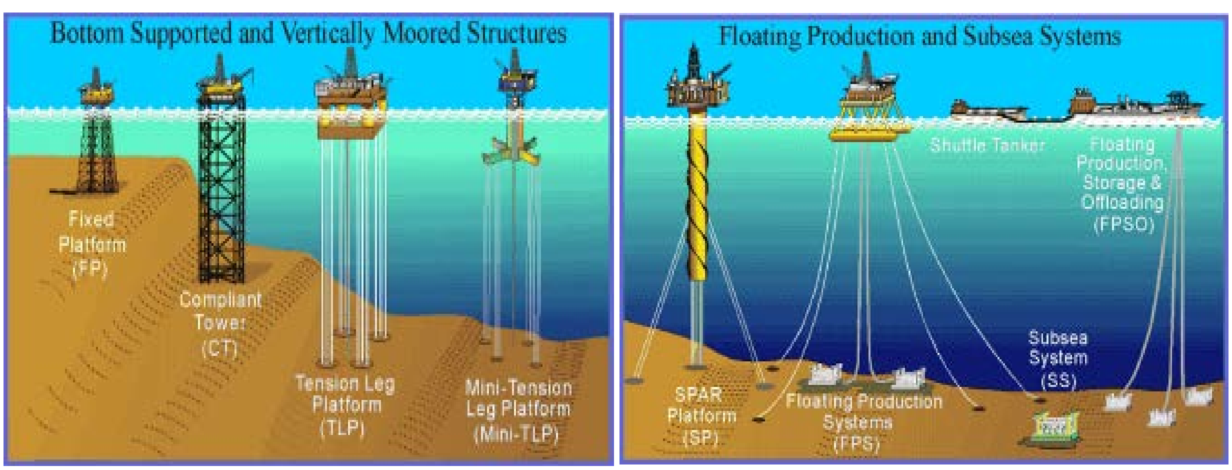


Figure 1. 1: Offshore Deepwater Systems in the Gulf of Mexico.
(BBSE Bureau of Safety and Environmental Enforcement for Offshore Structures, 2018)

However, the cost-effective oil and gas resources available has been moving to deeper waters, creating the need to used Floating Production Systems (FPS) which are connected to subsea systems to make production commercially viable.

The Semi-submersible units are part of the Floating Production Systems (FPS) and are normally equipped with production and drilling equipment. These types of floater are anchored in place with chains or ropes. They can be dynamically positioned by means of rotating thrusters. Semi-submersible units use wet-tree systems, meaning all the subsea production equipment is down in the seabed. (Bai & Bai , 2012) Production from subsea wells is transfer to the sea surface deck through production risers developed to accommodate floater motion. The FPS have been used in a range of water depths from 90 to 2300 meters. (BBSE Bureau of Safety and Environmental Enforcement for Offshore Structures, 2018)

Risers are important components in Offshore Oil and gas industry. As mentioned, these conductor pipes transfer oil and gas from subsea wells up to the top-side floating production platforms at sea surface. Riser concept should be designed having as main characteristics to be robust, safe and cost-effective. These criteria are intended for the riser systems to be able to withstand large motions of floating facilities in deep water and extreme conditions. There are mainly two kinds of subsea risers configurations: Rigid risers and flexible risers. A hybrid riser is obtained by bringing together these two types. (Bai & Bai , 2012). Four different kinds of production riser configurations that have been installed in offshore industry are: Steel catenary risers (SCR), Top tensioned risers (TTR), flexible risers and hybrid riser.

From its first installation on the Auger TLP located in the Gulf of Mexico (GoM) in 1994 (Phifer, Kopp, & Swanson, 1994). The free hanging steel catenary riser (SCR) has been the most adopted option for deepwater applications. This riser configuration comprises of a simple rigid steel pipe that hangs freely from the top-side facility up in the sea surface to the seabed. Its material properties are very well known and can be used with large diameters and a wide variation of wall thickness enable it to withstand high pressures and temperatures in deep water production. Nonetheless, the design of Steel Catenary Risers for large floater motions and harsh environment has been a considerable challenge. The principal problems facing in the design of SCRs in harsh environment are fatigue near hang-off and at touch down point (TDP). (Karunakaran & Jones, 2013)

Some solutions have being proposed to improve the performance of the SCR. Examples of modified SCRs are the Low Long Wave configurations (Karunakaran, Nordsve, & Olufsen, 1996), which handle better the excessive dynamic stresses caused by vessel heave motion. Steel Lazy Wave Riser (SLWR) applies this design. (Karunakaran, Seguin, & Legras, 2015). This riser is a more compliant or flexible configuration of SCR and varies from it by adding buoyancy modules in the lower part of the riser. SLWR optimized SCR by reducing extreme and cyclic stresses at the top end in the Touch Down Zone (TDZ). The wave shape of the SLWR is achieved by installing the mentioned buoyancy modules in the lower part of the riser.

Adding weights at the lower part of the SCR with the use of ballasts is another option to handle large platform motions. (Karunakaran & Jones, 2014). Weight Distributed Steel Catenary Riser (WDSCR) is a modification of SCR. This is a feasible robust riser concept for harsh environments from FPU's large motions. A screening of the downward velocity at the hang-off point made considering different riser configurations in the thesis "Feasibility Study of Selected Riser Concept in Deep Water and Harsh environment" (Gemilang, 2015), determined that a 10"- Internal Diameter with 25mm wall thickness free hanging riser can handle 2.6 m/s for the SCR, 3.2m/s for the WDSCR, and up to 6 m/s for the SLWR configuration.

Flexible risers are another type of riser configuration which have excellent performance achieving large curvature and dynamic motions of floating platforms produced by environmental loads. (Burgess & Lim, 2006). This type of risers is excellent for application in shallow waters and easy to install. Nonetheless, once in deep waters, flexible risers are limited due to practical and economical reasons. The main limitations are the maximum diameter, operating temperature and pressure. Adding to this, the number of vendors for flexible risers is limited.

Finally, other kind of riser is the hybrid riser. This riser is a combination of a flexible riser, called jumpers, and a vertical rigid or steel riser and subsurface buoyancy element connected between them. (Karunakaran, 2014). This type of configuration is aimed to provide a minimum transfer of moment to the rigid part of the configuration, decoupling the movements of the floating unit to the bottom part of the riser. The riser system is uncoupled to the floater motion due to the fact that the flexible jumpers connects the top end of the riser to the floater. With this, the riser will achieve better performance especially for fatigue. (Baarholm & Karunakaran, 2013). This hybrid configuration for risers have some issues which are that they are composed of many parts which made them very complex for installation and expensive.

1.2 Background study for residual curvature method

The Residual Curvature Method (RCM) is a cost-effective and straightforward technique to control lateral buckling applied using the straightener system during reel-lay installation to locally generate residual curvature sections in pipeline (Endal, Giske, Moen, & Sande, 2014). The idea is that residual curvatures are made at certain locations according to pre-design study in the pipeline (normally constant intervals). Pipeline buckling can be originated at locations were the residual curvatures were placed. Figure 1.2 illustrates a section of the pipeline with residual curvature.

The first user of this kind of method was the Skuld Project in the Norwegian continental shelf in 2012. The installation contractor was the company Subsea7. For this report, some simulations and calculations were made based on the dimensions of the pipeline used for Skuld project. In Figure 1.3, shows the reel pipelay vessel "Seven Oceans" which was in charge and successfully achieved the application of residual curvature method.

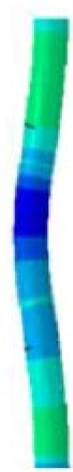


Figure 1. 2: Residual Curvature on a pipeline.
(Roy, Rao, Charnaux, Ragupathy, & Sriskandarajah, 2014)

Residual curvatures or un-straightened sections are created locally in the pipeline by adjusting the straightener component of the reel pipelay vessel (Figure 1.4) inserting the un-straightened sections in the vertical plane. In this way, the convex maximum point of the residual curvature sections will tend to roll as the pipeline goes down passing through the sagbend where the pipeline bends in the opposite direction. As the pipeline is being laid, work is done to roll and bend the pipeline when it goes from the vessel to the sea bottom. The total work done to achieve this is used to estimate pipeline roll angle in the touch down point. (Endal, Giske, Moen, & Sande, 2014)

Residual curvature is an effective method of control lateral bulking and specified several means of adjust pipeline to seabed topography and recognize that the importance of residual curvature includes pipeline stability during installation, in relation to rolling. (Endal, Nystrøm, & Lyngsaunet, 2015)

Figure 1. 3: Subsea7 vessel for Reel-Lay. "Seven Oceans".
(Subsea7, 2015)

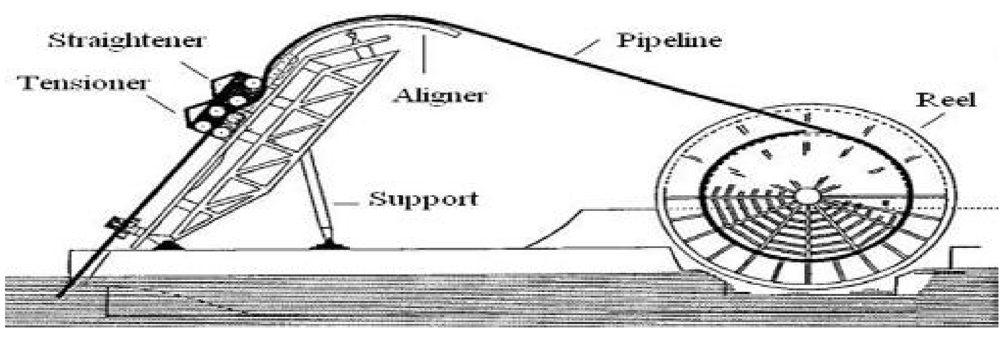


Figure 1. 4: Offshore pipeline installation with the use of the Reel-lay method.
(Hu, Duan, & Lui, 2012)

The potential application of residual curvature method in the installation of Steel Catenary Risers was recognized by Edal and Nystrøm. (Endal & Nystrøm, 2015)

1.3 Justification, Objectives and Scope

Steel Catenary Risers concept has issues and limitation regarding its use in conjunction with floating production such as Semisubmersibles in deep and ultra-deep waters. A substitute configuration for the Steel Catenary Riser is the implementation of Weight Distributed SCR's (WDSCR) and Steel Lazy Wave Riser (SLWR) and; but these configurations encounter some disadvantages such as more complex installation, the use of additional buoyancy or weight distributed modules close to the seabed and more maintenance issues related with marine growth and more components include, with all this mentioned, costs and installation time increase.

This project focuses on the application of the residual curvature method (addition of un-straightened sections) to Steel Catenary Riser installed with reel-lay technique. The idea is to determine the issues and merits encounter in the application of residual curvature method to a steel catenary riser RCSCR for deep water and extreme conditions such a Hurricane. Particularly, how the application of this method improves or deteriorate the riser response for maximum effective tension, compression, bending moment and utilization considering Load Resistance Factor Design (LRFD) described in the standard DNV-OS-F201. This study is achieved with the help of a finite element method (FEM) model made in OrcaFlex.

1.3.1 Objectives

- Assessment of the selected Deepwater Free Hanging Steel Catenary Riser configurations considering the ability to handle large floater motion.
- Implementation of Residual Curvature Method on Steel Catenary Riser
  - Describe riser design theory, riser installation methods and residual curvature theory in Reel-lay method.
  - Describe software to be use in the development of the model.
  - Construct a riser model and implement Residual Curvature method.
- Perform a parametric study for the most optimum geometries and configuration for the implementation of sections with residual curvature on Steel Catenary Riser.
- Compare the analytical results of the implementation of Residual curvature method on the SCR and WDSCR configurations against the conventional SCR

and WDSCR in terms of capability to handle with floater motion by determining the maximum downward velocity at the hang-off point for the different riser configurations and evaluate strength as well as fatigue performance.

1.3.2 Scope

The scope of the thesis is described as follows:

- Chapter 1. This chapter provides introduction, background, scope and purpose for this study.
- Chapter 2. Present a description of deepwater riser systems. Risers systems and its development are discussed with focus on free hanging riser configurations.
- Chapter 3. Describe and discuss the code check used in this study for riser system design.
- Chapter 4. This chapter specifies the theory on Residual Curvature Methods and its applications.
- Chapter 5. This chapter presents the basis design. Here, analysis design and methodology are included. Moreover, background in riser analysis and marine technology and Sea conditions for Gulf of Mexico are discuss.
- Chapter 6. This chapter presents an overview of fabrication and installation for risers.
- Chapter 7. Provide and discuss extreme response study for the different riser configurations with the aim to verify the specifications, parametric study and results for ultimate limit state (ULS) and accidental limit state (ALS) focusing the attention in the capabilities of the riser with residual curvature.
- Chapter 8. This chapter specifies and discusses fatigue analyses for SCR and RCSCR configurations to verify the specifications and requirements for fatigue limit state (FLS).
- Chapter 9. This chapter addresses conclusions and recommendations obtained in this study.

Figure 1.5 describes the constraints of thesis with a project triangle used in project management by defining the boundaries such as:

- **Time:** Signing contract with the company to the thesis's deadline.

- **Scope:** Goals, information available on the topic of Residual Curvature Method and its application to risers.

- **Resources:** Software, licence limitations, limitation in number of simulations with use of the network dongle option instead of physical dongle, lack of software's training, computer storage capacity that made it necessary to use external hard drive, computer and network security features and limitations when using external hard drive and pen drive.

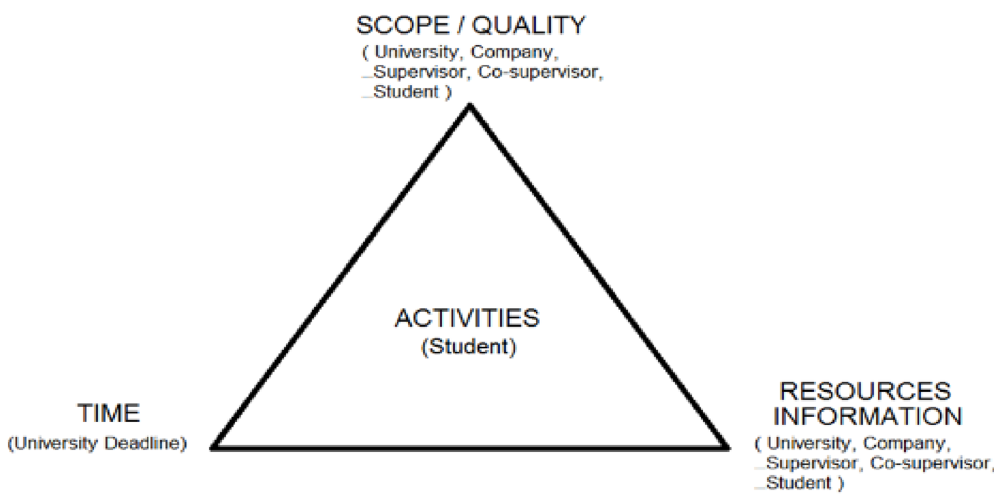


Figure 1. 5: Thesis Project Triangle for Scope

1.3.3 Justification

With increasing oil prices, the implementation of projects is subjected heavily of the costs. The request for cost saving and optimized feasible solutions in the offshore oil and gas industry is an utmost importance in the last years. New or optimized riser configurations have been studied for achieving this goal. The cost of implementation for the residual Curvature Method on pipeline and on a Steel Catenary Riser will be shown to be negligible and can be part of the riser installation process.

Chapter 2. Deepwater Riser Systems

2.1 Definition and Description

Riser systems are vital components to produce oil and gas for offshore fields. A riser system is defined as the interface between the seabed and the topside facility. The riser system must withstand the loads from current and waves safely and contain the internal flow and pressure. According to the standard (API RP 2RD, 2006), the riser must be able to maintain its structural integrity and be globally stable during the entire operational life cycle of the offshore developments.

Riser are divided into the flowing concepts (Karunakaran, 2014) and (Subsea7, 2015):

- Production Riser
- Drilling Riser
- Export Risers
- Water/Gas Injection risers

Floating drilling risers are used on drilling semi-submersibles and ships. As the water depth are higher, integrity of drilling riser is a critical issue. This rigid type of riser is involved in exploration, completion, workover and plugging activities. This riser is only temporary used while it is in drilling or well intervention activities (Bai & Bai , 2012).

An oil and gas production riser system is made of conductor pipes connected from topside on sea surface to the wellhead or production equipment at seabed. It is the main element for transporting fluids to and from the vessel in the subsea production system. It is the most complex components in the production system (Bai & Bai , 2012). There exist fundamentally two kinds of subsea production risers: Rigid risers and flexible risers. A hybrid riser is attained by integrating these two risers configurations.

Figure 2.1 illustrates main components of the production riser system. There are two essential parts in a production riser: Riser Body and Riser Interface.

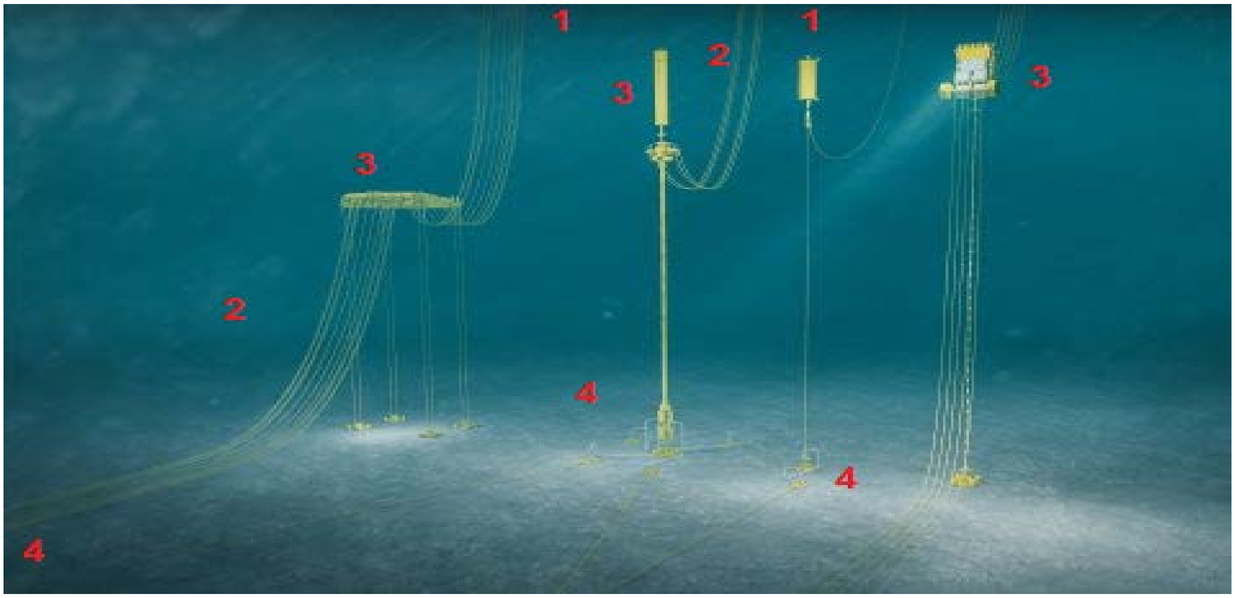


Figure 2. 1: Components of different riser configurations.
(Subsea7, 2015)

In Figure 2.1, shows different riser configurations, the main components are:

1. Top Interface
2. Conduit
3. Buoyancy module
4. Bottom interface

The riser body is the conduit and can be made of metal or flexible materials. It can serve also as a mooring element. This metal pipe in normally API 5L material which can be segmented or continuous. The system interface depends on multiple factors such the type of floater or subsea equipment is going to be attached.

The riser arrangement needs to be able to withstand external and internal loads, additionally, it must be design with enough safety margin to cope with these loads. The main design driver for riser are (Karunakaran, 2014) :

- Floater type
- Floater motions
- Water depth
- Environmental conditions such as current and waves
- Design pressure and temperature
- Overall heat transfer
- Type of fluid, for instance corrosive

- ➢ Vortex Induced Vibrations VIV
- ➢ National limitation and regulations.

Production risers can be described inside the following four categories according to the behavior of the material (rigid, flexible, combination of both) and components (Bai & Bai , 2012):

- ➢ Rigid Steel Catenary Riser
- ➢ Top Tensioned Riser TTR
- ➢ Flexible Risers
- ➢ Hybrid Risers

Similarly, risers can be categorized depending on the amount of motions from the floater they are subjected. Commercially speaking some companies also used this classification. In this way, riser systems fall into two categories: those coupled directly to the host facility, and uncoupled systems which in most cases are connected by flexible jumpers. The terms coupled and un-coupled are used in this case following (Karunakaran, 2014) and (Subsea7, 2015) description:

- **Coupled riser system:** Riser are connected to the floater and experience or are exposed to the full floater motions. For instance (Subsea7, 2015):

    - Steel Catenary Risers (SCRs)
    - Weight-Distributed SCRs (WDSCR)
    - Steel Lazy-Wave Risers (SLWRs)
    - Flexible Riser Systems

- **Un-Coupled riser system**: This are risers connected to the floater through jumpers which are flexible, and this flexible component experience the full floater motions. For this case, the riser itself will not experience completely the floater motions. It is either fully or partially isolated from the floater motions. For example:

    - Single Hybrid Riser (SHR)
    - Grouped Single Line Offset Riser (SLOR)
    - Hybrid Riser Tower (HRT)
    - Tethered Catenary Riser (TCR)
    - Catenary Offset Buoyant Riser Assembly (COBRA)

2.2 Rigid Catenary Risers

Known also as free hanging risers, can be describe as rigid steel risers with sections of pipe that are joined together by welding, flanges and threats. This kind of riser is coupled to the floater which mean that they experience full motions. The design rigid riser is challenging due to the nature of the dynamic forces to which are subjected. Here three types of risers will be described: Steel Catenary Riser SCR, Weight Distributed SCR (WDSCR) and Steel Lazy Wave Risers (SLWR)

2.2.1 Steel Catenary Riser

The Steel Catenary Riser is a single conduit pipe, which is attached directly to the floater or fixed surface facility, it is hanged freely on its own weight from close to vertical direction (known as hang-off top angle) on the sea surface to a horizontal plane at the seabed. The Augur platform is the first floating production facility to install an SCR with 870m water depth in the Gulf of Mexico in 1993 (Bai & Bai , 2012). Two 12" lines were installed for oil and gas export. Since this, SCR have been used for deeper waters developments such as in Brazil and offshore west Africa.

According to Bai et al. 2012, SCR is a cost-effective solution for hydrocarbons export and for water injection lines on deepwater fields, where a large diameter flexible riser present economic and technical limitation. An SCR is a free hanging riser with no intermediate buoyancy or weighted modules. Figure 2.2 illustrates a typical SCR Configuration.

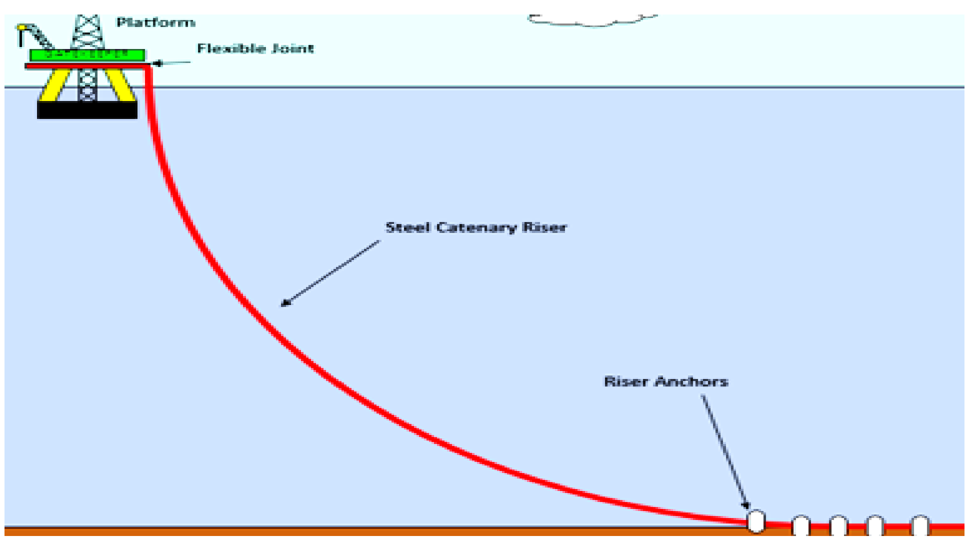


Figure 2. 2: SCR Configuration
(Gate Energy, 2015)

The riser is connected to the topside by a flexible joint as illustrated in Figure 2-2. The riser consists of steel segments that are welded together, its construction characteristics such as well thickness and steel quality is selected based on the following specification:

- ✓ Water depth
- ✓ External pressure
- ✓ Fluid and reservoir properties: Temperature, pressure and corrosive capabilities.
- ✓ Top side weight capabilities
- ✓ Cost and installation methods
- ✓ Environmental conditions: Current, waves
- ✓ Fatigue Performance

Steel Catenary risers are used from 800 to 2800m of water depth, they have been applied in Tension Leg Platforms TLP, SPAR floaters in Gulf of Mexico and Semisubmersibles in Brazil. Its method of installation goes from J/S lay to reeling. Some characteristics of the SCR is that used low cost material, can be implemented in High pressure/Temperature fields. It is feasible to perform internal inspections throughout pigging; SCR uses well known material properties and some method of insulation can be implemented such as pipe-in-pipe (Karunakaran, 2014).

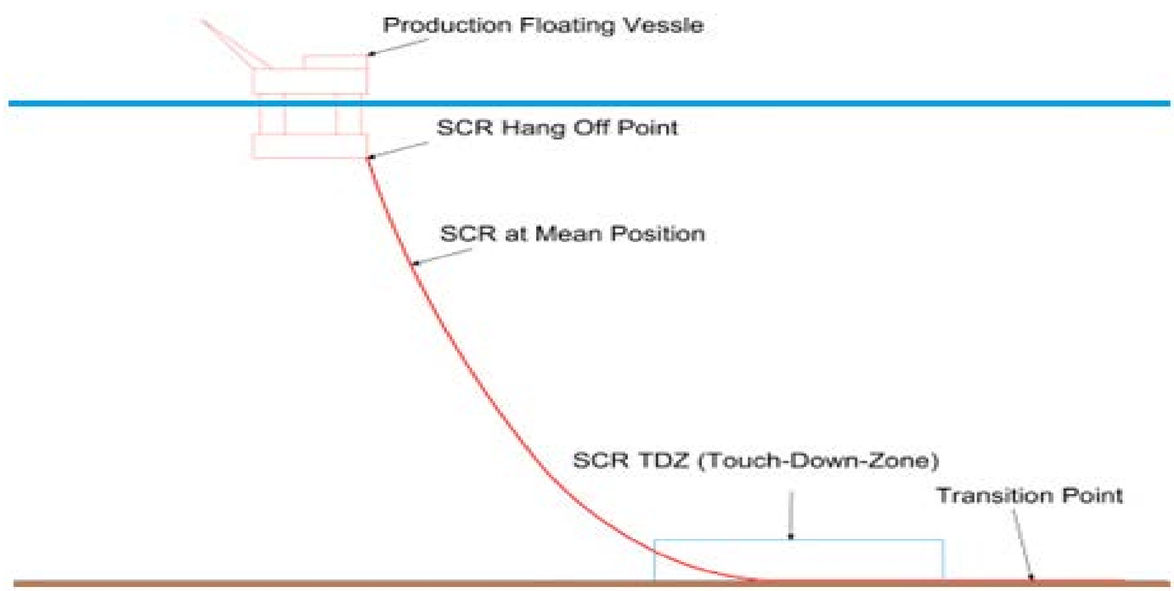


Figure 2. 3: Steel Catenary Riser. Hang off point and TDZ

As specified by Bai et al. 2012 and consulting from Oilfield Wiki, “the SCRs are sensitive to current and waves given the low of effective tension along the riser. The fatigue damage induced by the Vortex-Induced Vibrations VIV can make the riser fail”. Installation of VIV suppression devices are normally necessary, some of the devices used are the helical stakes and fairing which help to decrease the vibration to an allowable level (Oilfield Wiki, 2019). Figure 2.3 illustrates the different areas in the SCR.

2.2.2 Weight Distributed Steel Catenary Riser

The Weight Distributed Steel Catenary Riser WDSCR configuration is an improvement of the SCR. The weight distributed section enhances the performance of the SCR to harsher environments (Subsea7, 2015). For this configuration, variation in weight of the riser is performed by applying different density coatings or by attaching ballast elements at certain location along the arc-length of the SCR to reduce the stress in the touch down point and improve the fatigue performance. For obvious reasons, its disadvantage is the increase in top tension. (Karunakaran & Jones, 2014). Figure 2.4 Illustrates the configuration of a WDSCR.

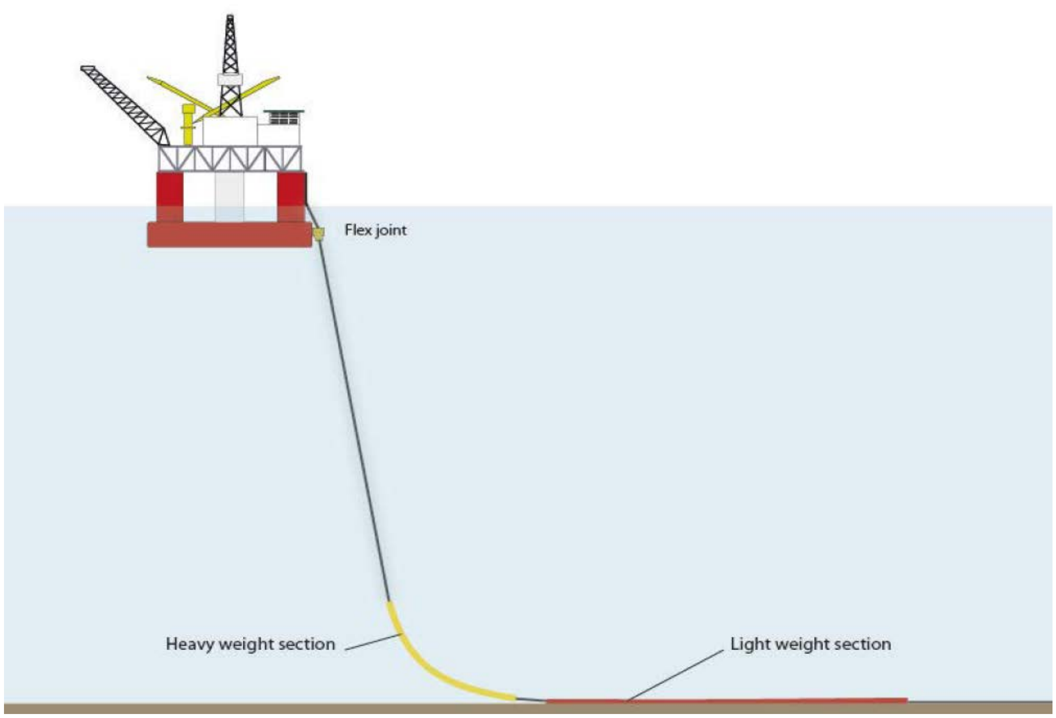


Figure 2. 4: Weight Distributed SCR concept
(Karunakaran & Jones, 2014)

Normally, the external coating is used on risers for corrosion protection, mechanical protection and thermal insulation. But in this case, the external coating is applied for the weight distribution by considering its density and thickness in the section. Some issues appear in this case, such as hydrostatic creep and water absorption. Similarly, the addition of weight can be obtained by suing ballasts in the section. These ballast modules comprise of an internal clamp and split ballast element together with a fastening system.

2.2.3 Steel Lazy Wave Riser

Steel Lazy Wave Riser SLWR is a riser that has a geometry of a low long wave near the bottom. This configuration was first mentioned in the article "An Efficient Metal Riser Configuration for Ship and Semi Based Production Systems" (Karunakaran, Nordsve, & Olufsen, 1996). Even though this riser is directly attached to the floater, it successfully decoupled the motions from the floater in the TDP. The addition of buoyancy modules close to the seabed create the low long wave. As mentioned, this riser configuration manages to decouple the forces induces by the floater motion, thus enhance the fatigue life and performance in comparison with the conventional SCR. The first SLWR was installed in BC10 Field in Brazil in 2008 (Figure 2.5), and since then, it has gain popularity due to that its ability to decrease top tension, robust design for extremes, good fatigue performance and lower payload on the floater. (Karunakaran, Frønsdal, & Baarholm, 2016)

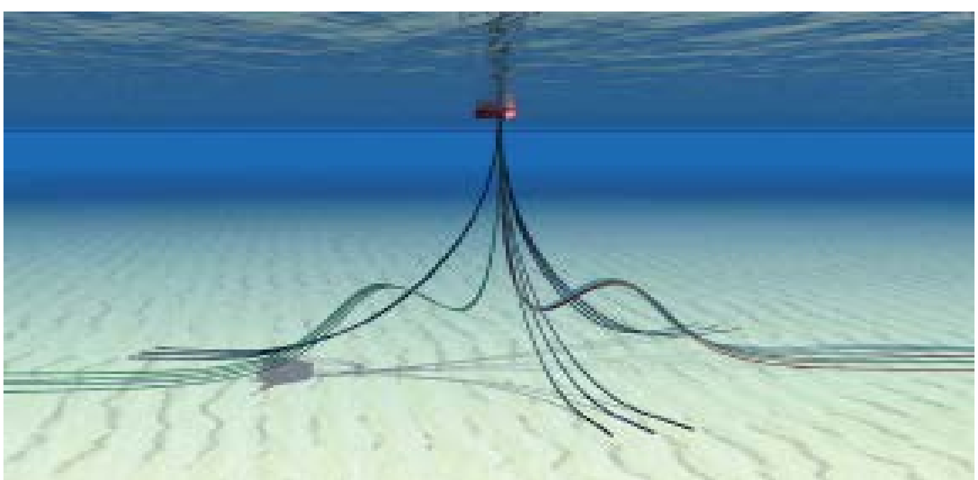


Figure 2. 5: Steel Lazy Wave Riser, BC-10 field. Brazil
(Subsea7, 2015)

A diagram with a description of SLWR is illustrated in Figure 2.6, the arc-length is divided in four sections (Hoffman, Yun, & Modi, 2010):

- Upper Catenary Section:
    - The upper section spread as the conventional SCR and is supported by the floater and is connected to the hang-off point. This section is most of the riser length.
- Buoyancy Section:
    - The buoyancy section is the part that provides the lift or buoyancy force and it is where the buoyancy modules are attached.
- Lower Catenary Section:
    - The lower catenary section is the part of the riser from the end of the buoyancy section to the touch down point on the seabed.
- Bottom Section:
    - The bottom section is the part that goes through the touch down point to the riser-flowline transition point in the seabed.

Some project which have installed this configuration are: BC-10 Brazil (1800 m) as mentioned, Presalt Brazil (2200m) and stones GoM (2900).

According to Hoffman et al 2010, the vertical distance between the highest point and the hog bend and the lowest point on the sag bend is also known as the wave height of the riser. Likewise, this configuration significantly improves dynamic behavior performance in comparison with SCR. But at the same time, it is worth mentioning that this configuration has some drawbacks:

- ✓ High fabrication and installation costs
- ✓ Addition of Buoyancy modules which make more complex the design and implementation.
- ✓ Expensive design.
- ✓ Issues with the buoyancy modules.

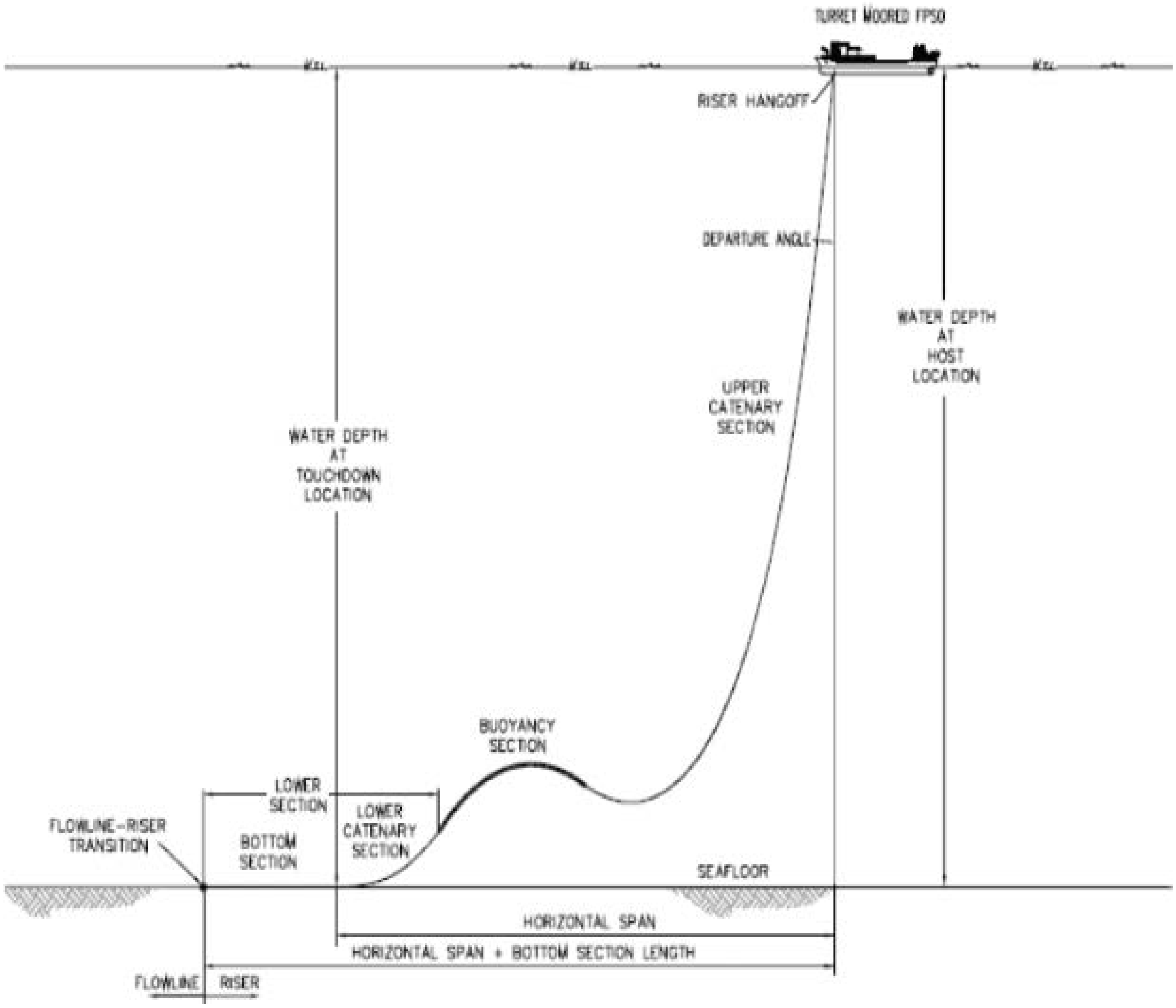


Figure 2. 6: SWLR Configuration
(Hoffman, Yun, & Modi, 2010)

2.3 Flexible Risers

Flexible have proven to be a successful solution for deepwater and shallow water riser as well as flowline system (Bai & Bai , 2012). Flexible risers are applied for production and export purposes and are consider coupled systems. This type of risers are conductor pipes with large axial stiffness and low bending stiffness. This configuration is considered a coupled riser solution. They are made up of several individual layers as shown in Figure 2.7 and are divided in two categories: Bonded and un-bonded. The bonded type is used for short distance such as topside jumpers and the un-bounded is the most widely used for application in deep waters. Some flexible riser has been installed in water depth as far as 3000m in 2014. (Luppi, Cousin, & O'sullivan, 2014)

The cross section of typical un-bonded flexible pipe is presented in the Figure 2.7, it is made up of a metallic inner carcass to support external overpressure, and plastic pressure sheath to contain the producing fluids. The Zeta spiral for pressure containment, a thermoplastic sheath to reduce friction between tension armour and Zeta spiral. The tension armour is used to take the axial forces and the external sheath is used for abrasion protection or in this case an outer-wrap interlocked stainless steel carcass.

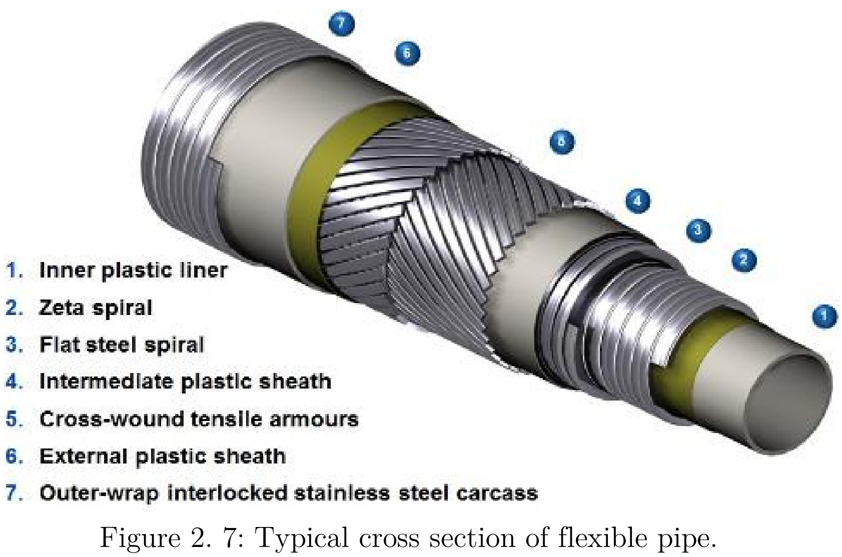


Figure 2. 7: Typical cross section of flexible pipe.
(TReK STS, 2016)

This type of risers has limitation for deep waters mainly due to the increase of external pressure, the production bore will be restricted for large depths (Carter & Ronald, 1998). Flexible risers are considered easy to install in comparison with other riser solutions, likewise there is an extensive track record for this kind of risers. (Karunakaran, 2014)

2.4 Hybrid Risers

The idea of a hybrid riser was developed considering the design implemented by the top tensioned risers TTRs. The TTRs are used on SPAR and TLP Risers because they cannot be subjected to large dynamic forces. The hybrid risers principal characteristic is the ability to handle relative motion between a floating unit and a rigid metal riser TTR, by connecting these two structures with a flexible jumper (Bai & Bai , 2012). Hybrid riser system combined rigid risers and flexible risers and are considered an un-coupled kind of riser because the part of the riser that is attached to the seabed is not experiencing floater motions.

The main examples of Hybrid Risers are:

- Single Hybrid Riser (SHR)
- Hybrid Riser Tower (HRT)

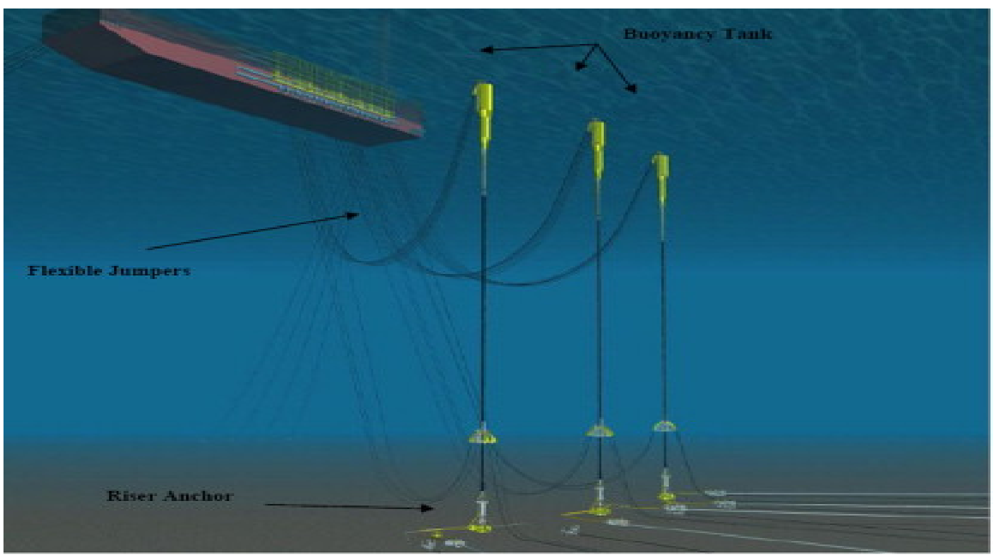


Figure 2. 8: Hybrid Riser Tower configuration
(Bai & Bai , 2012)

Figure 2.8 illustrate a bundle hybrid riser. A buoyancy tank is used to support the rigid part which is attached to suction anchors or gravity base anchors and flexible joints to the seabed. At the top, the flexible jumpers connect the buoyancy tank to the floater.

Other type hybrid risers concept are (Subsea7, 2015) (Karunakaran, 2017):

- Buoyancy Supported Riser (BSR):
  This system connect a group of SCRs with flexible jumpers with a large buoyancy module linked to seabed throughout a tether.

- Grouped Single Line Offset Riser (SLOR):

The Grouped SLOR is usually used for deepwater applications. According to Riser Technology catalog of Subsea7 “They are an 'open Bundle' riser solution developed specifically to optimize the riser to vessel interface, production vessel approaches and access for riser inspection and maintenance”. The Grouped SLOR have huge potential application for large deepwater developments, that normally have a intricated and complex seabed layout. (Subsea7, 2015)

- Catenary Offset Buoyant Riser Assembly (COBRA):

COBRA concept was developed by Karunakaran and Baarholm in 2013. It is a modification of the hybrid riser concept. It combines the flexibility merits of the hybrid concept with the simplicity and economic characteristics of the SCR. The concept is an assembly SCR connected to a sub-surface buoyancy tank which is tethered down to the seabed throughout a mooring line, and a flexible jumper connected to the floater (Karunakaran & Baarholm, 2013)

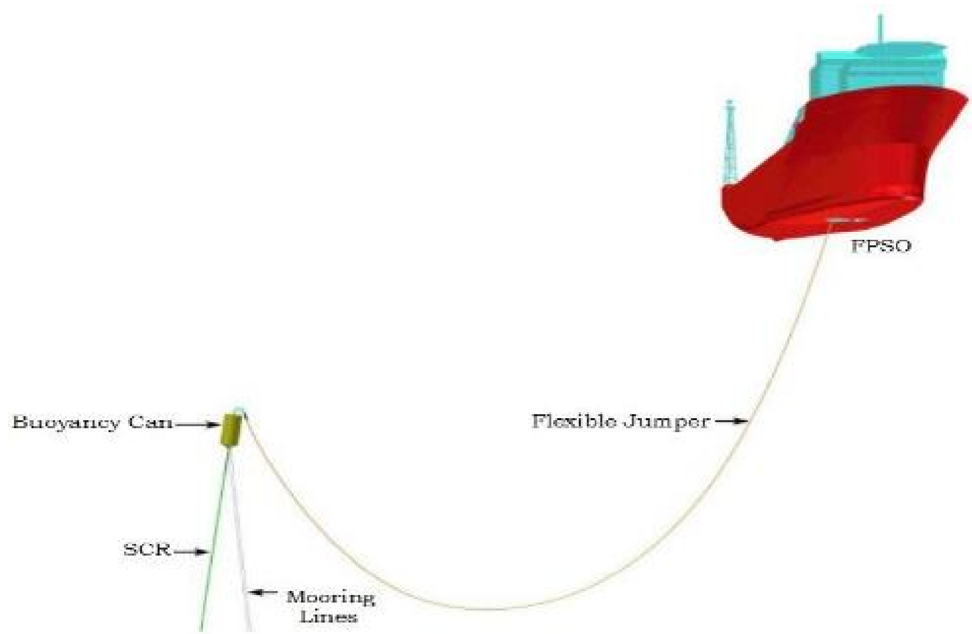


Figure 2. 9: Typical COBRA Riser Arrangement
(Karunakaran & Baarholm, 2013)

Chapter 3. Code for Riser design

3.1 Introduction

For the standards in the offshore industry, there are two main design criteria to meet and follow, the Load and Resistance Factor Design (LRFD) and the Working Stress Design (WSD)

Safety and structural integrity of risers that work with floating production units has been designed to meet the requirements of the Working Stress Design criteria according to standards like for example API RP 2RD, by implementing a unique safety factor (API RP 2RD, 2006). This method considers all uncertainties by use of one single factor applied to the nominal yield strength, in this case, the safety margin and reliability will depend on the chosen value for the factor (Karunakaran, 2014).

Working Stress Design has been implemented for riser concepts with extensive record; however, the safety level of the design becomes different depending on the type load condition and currently is considered to be too conservative not taking full advantage of the potential of the material. However, the design of riser has become more demanding as risers are being used in deeper water and harsher conditions, these risers require more scientific based standards to optimize their used and accomplish more reliable level of safety. Thus, the use of ore specific standards is needed to accomplish this.

DNV-OS-F201 standard was developed to take into account different uncertainties involve in the riser design (Katla, Mork , & Hansen, 2001). According to Katla et al, this standard can be applied for modifications, operation and upgrading of existing risers, and is aimed to work as a guideline for designers, operators and manufacturer. DNV-OS-F201 includes LRFD and WSD approaches. The partial safety factors for the strength and load point of view in the LRFD method are based on probability distribution for load and resistance with the help of reliability studies as well as adjusted to obtain a high reliability without putting in risk the system's safety and taking full advantage of the material considering uncertainties (Kavanagh, Lou, & Hays, 2003).

The analysis of the Utilization Factor in this thesis project will consider the equations describe by Standard DNV-OS-F201. (DNV , 2010a)

3.2 Offshore Standard for Dynamics Riser DNV-OS-F201

The DNV-OS-F201 is a standard or code that supply requirements, guidance and criteria for the analysis and structural design of riser systems subjected to static as well as dynamic loading due to current, wind and waves for applications in the oil and gas offshore industry. (DNV , 2010a)

The design parameters according to this standard provides the latest limit state design for dynamic risers, which nowadays inside the oil and gas industry, it has become a routine method of common acceptance. The merits of using this standard are summarize as follows (DNV , 2010a):

- Consistent safety level for the riser solution considering flexible limit state design principles
- Integration of safety class methodology together with acceptance criteria to consequences of failure
- Reach the limit in the state functions for the Load and Resistance Factor Design (LRFD) approach considering adjusted reliability functions to safety factors. Likewise, consider the simple more conservative Working Stress Design (WSD) approach.
- Provides guidance and requirements for efficient global analysis and propose a consistent connection between design checks (failure modes), load conditions and load effects.

The general description for the standard is:

Design response < Design Resistance

The goal of this standard is that design, materials, fabrications and other aspects of the riser lifecycle are safe and achieved considering public safety and protection of the environment. Figure 3.1 describe the safety philosophy integrating different factors.

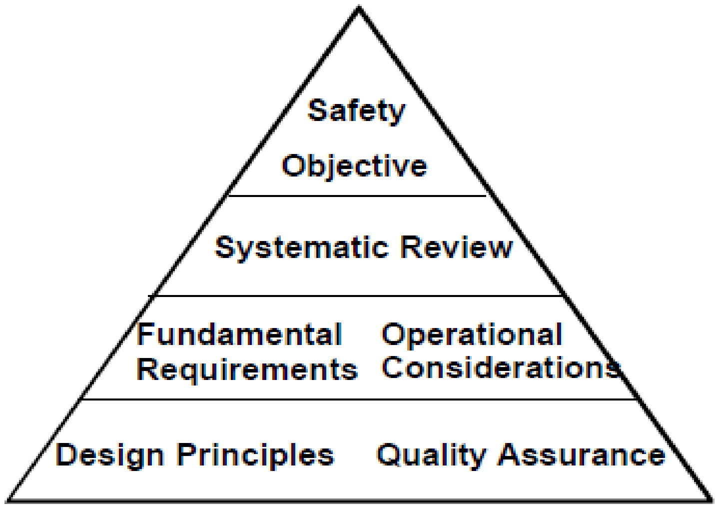


Figure 3.1 Safety Hierarchy for DNV-OS-F201

According to DNV, 2010 "The Load and Resistance Factor Design (LRFD) is a reliability-based approach with partial safety factors used to guarantee that the effects of the factorized design loads do not exceed the factored design resistance for the corresponding limit states".

Design criteria for the limit states is provide as follows:

- Ultimate Limit State (ULS): In this limit state involve the structural integrity of the risers. The riser needs to remain intact and avoid failure; however, not necessary with the capacity to operate since the consequences are severe. In operational condition, this value is equal to the maximum resistance against the applied loads with 10^{-2} as the annual probability of exceedance.

  For Limit state this include:

  - Bursting (internal pressure)
  - Propagating buckling
  - Global buckling
  - Unstable fracture and gross plastic deformation
  - Hoop buckling (collapse)
  - Gross plastic deformation and local buckling
  - Gross plastic deformation, local buckling and hoop buckling

- Serviceability Limit State (SLS): Involve the disruption of use of the riser as intended.

  This Limit state include:

  - Excessive ovality of cross section (initial or progressive)
  - Mechanical function
  - Excessive angular response

- Accidental Limit State (ALS): Similar description as mentioned for ultimate limit state; however, apply for accidental loads. Accidental limit state involves damage or failure due to unusual, accidental, or unplanned loading conditions such as: Dropped objects (impact lading), Incidental overpressure, explosion and fire, severe earthquakes or environments.
  This Limit state include: The Same as mentioned in serviceable and ultimate limit states.

- Fatigue Limit State (FLS): An ultimate limit state due to damage from cyclic loading or excessive fatigue crack growth. Sources include: Currents, waves, slugging. The limit state is Fatigue failure

A summary as a flow diagram of the ULS design method is presented in Figure 3.2, this design approach is summed up as follows:

- Identify all the limit states and design situations, for instance FMEA, HAZOD and design checks.
- Take into account all applicable loads
- Execute preliminary riser design and static pressure, design checks for parameters such as bursting, hoop buckling and propagating buckling
- Set up load conditions
- Define the generalized load effect
- Perform riser analysis with the appropriate model
- Use of environmental and response statistics to establish extreme generalized load effects
- Check that the limit state is not exceeded

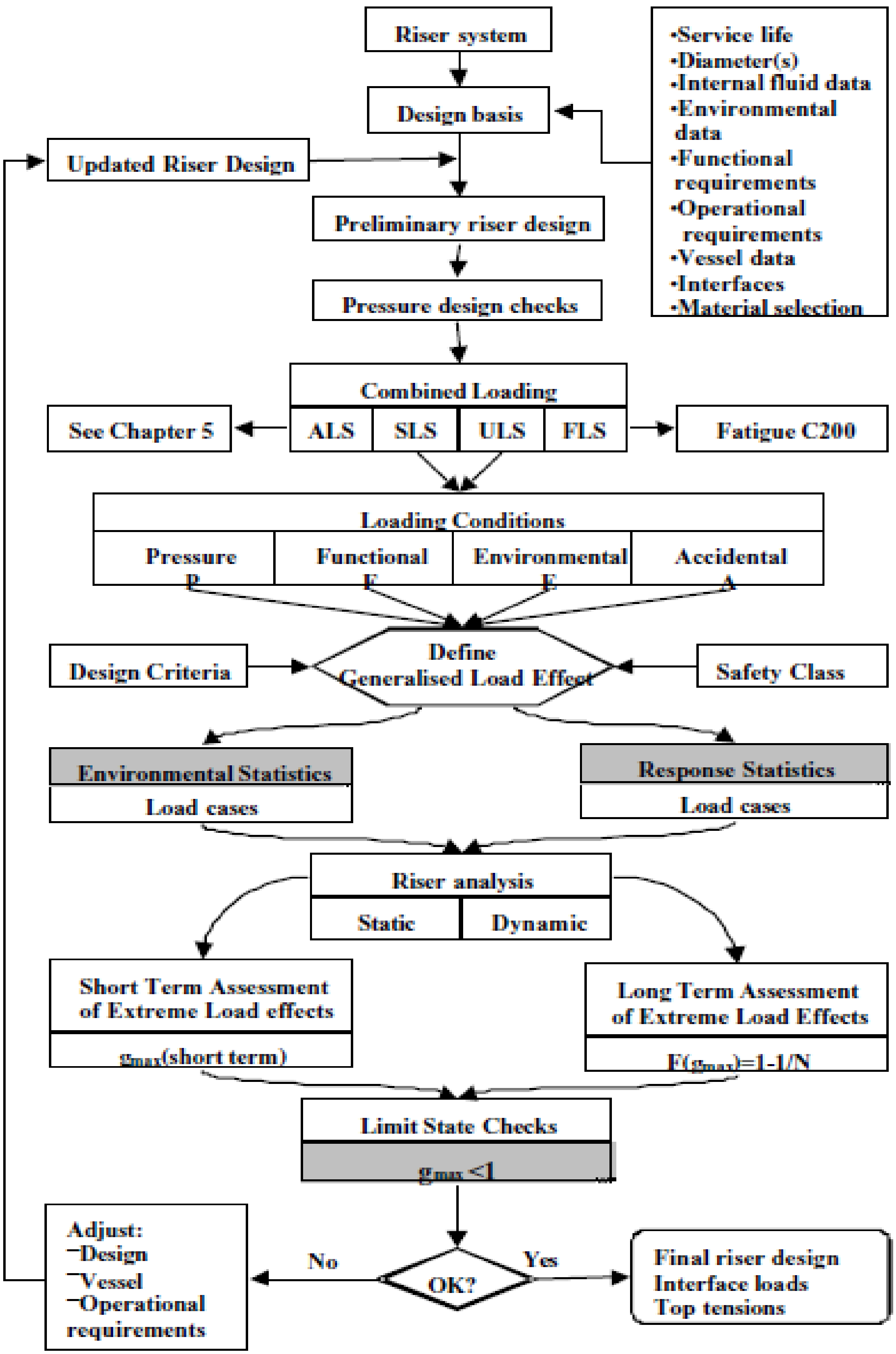


Figure 3.2: Analysis Methodology- Design approach (DNV, 2010a)

3.3 Load and Resistance Factors for design

3.3.1 DNV-OS-F201 Load Effects

First, it is necessary to categorize the safety classes. Riser design must consider the potential failure consequences. This is mentioned in the Table 3.1 from the DNV-OS-F201 classification of safety classes (DNV , 2010a).

Table 3. 1: Safety classes classification

Safety class	*Definition*
Low	Where failure implies low risk of human injury and minor environmental and economic consequences.
Normal	For conditions where failure implies risk of human injury, significant environmental pollution or very high economic or political consequences.
High	For operating conditions where failure implies high risk of human injury, significant environmental pollution or very high economic or political consequences.

Extreme load effects consider load effect factors with enough margin when checking the utilization factor of the cross-section of the riser, regarding effective tension and bending moment in the combined loading criteria. The load effects are described in terms of pressure, environmental, functional and accidental load effects which are categorized in the DNV-OS-F201 as illustrated in Table 3.2 (DNV, 2010a).

Table 3. 2 Description of loads.

F-loads	*E-loads*	*P-loads*[7)]
Weight and buoyancy[6)] of riser, tubing, coatings[6)], marine growth[2)], anodes, buoyancy modules, contents and attachments Weight of internal fluid Applied tension for top-tension risers Installation induced residual loads or pre-stressing Pre-load of connectors Applied displacements and guidance loads, including active positioning of support floater Thermal loads Soil pressure on buried risers Differential settlements Loads from drilling operations Construction loads and loads caused by tools	Waves Internal waves and other effects due to differences in water density. Current Earthquake[4)] Ice[3)] Floater motions induced by wind, waves and current, i.e.: — Mean offset including steady wave drift, wind and current forces — Wave frequency motions — Low frequency motions	External hydrostatic pressure Internal fluid pressure: hydrostatic, static and dynamic[5)] contributions, as relevant Water Levels

NOTES

1) Accidental loads, both size and frequency, for a specific riser and floater may be defined by a risk analysis.
2) For temporary risers, marine growth can often be neglected due to the limited duration of planned operations.
3) Ice effects shall be taken into account in areas where ice may develop or drift.
4) Earthquake load effects shall be considered in the riser design for regions considered being seismically active.
5) Slugs and pressure surges may introduce global load effects for compliant configurations.
6) Includes also absorbed water.
7) Possible dynamic load effects from P-loads and F-loads shall be treated as E-loads, e.g. slug flow.

The listed factors for the limit states are presented in Table 3.3 (DNV, 2010a) .

Table 3. 3: Load effect factors table

Limit state	*F-load effect*	*E-load effect*	*A-load effect*
	γ_F	γ_E	γ_A
ULS	1.1 [1)]	1.3 [2)]	NA
FLS	1.0	1.0	NA
SLS & ALS	1.0	1.0	1.0

NOTES

1) If the functional load effect reduces the combined load effects, γ_F shall be taken as 1/1.1.
2) If the environmental load effect reduces the combined load effects, γ_E shall be taken as 1/1.3.

3.3.2 DNV-OS-F201 Resistance Factors

Two safety factors are used in the combined loading case. The first is related to the safety class of the riser, γ_{SC}, and the second consider all the material and resistance uncertainties, γ_m.

Consequence of failure that may affect human life, environmental and economic loses defines the safety class, these fall inside the following categories: Low, Medium or High. The safety class is defined founded on consequence of failure. Safety class and material resistance factors are listed in Tables 3.4 and 3.5 (DNV, 2010a).

Table 3. 4: Safety class resistance factors

Safety Class Resistance Factor, γ_{SC}		
High	Medium	Low
1.26	1.14	1.04

Table 3. 5: Material resistance factors

Material resistance factor, γ_m	
SLS & FLS	ULS & ALS
1.0	1.15

3.4 Ultimate Limit State ULS

The riser in Ultimate Limit State must be design against relevant failure modes mentioned in the description for ULS chapter 3.2.

3.4.1 Bursting

Riser subjected to net internal over pressure must be design in a way that its integrity remains intact during its lifecycle and to meet the following criteria for the entire cross sections along the riser arc-length:

$$(p_{li} - p_e) \leq \frac{p_b(t_1)}{\gamma_m * \gamma_{sc}} \qquad Eq.3.1$$

Having that:

$p_{li} = p_{inc} + \rho_i * g * h$; Local incidental pressure

ρ_i : Density of internal fluid

$p_{inc} = 1.1 * p_{design}$; Incidental pressure

p_e: External pressure

$p_b(t_1) = \frac{2}{\sqrt{3}} * \frac{2*t_1}{D-t_1} min\left(f_y; \frac{f_u}{1.15}\right)$; Burst resistance

$t_1 = t_{nom} - t_{fab}$; Local incidental pressure

t_{nom} Specified or nominal wall thickness

t_{fab} Construction negative tolerance

3.4.2 Hoop Buckling

When exposed to external overpressure, the riser needs to be designed to meet the next criteria:

$$(p_e - p_{min}) \leq \frac{p_c(t_1)}{\gamma_m * \gamma_{sc}} \qquad Eq.3.2$$

Where:

p_{min}: Minimum internal pressure

$p_c\ (t)$ Resistance against hoop buckling; according to the standard as:

$$(p_c\ (t) - (p_{el}\ (t)) * (p_c^2(t) - p_p^2(t)) = p_c\ (t) * p_{el}\ (t) * p_p\ (t) * f_0 * \frac{D}{t}$$

Considering that:

$p_{el}\ (t) = \frac{2*E*\left(\frac{t}{D}\right)^2}{1-v^2}$; Elastic collapse pressure

D Pipe diameter

t Wall thickness of pipe

E Elastic modulus

v Poisson ratio

$p_p\ (t) = 2 * \frac{t}{D} * f_y * \alpha_{f\ ab}$; Plastic collapse pressure

f_y Material yield strength

$\alpha_{f\ ab}$ Manufacturing process reduction factor

$f_0 = \frac{D_{max} - D_{min}}{D}$; Original ovality of riser, should not be less than 0.5%

3.4.3 Combined Loading Criteria

Riser subjected to combined load of effective tension, bending moment and net internal overpressure must satisfy the following equation (DNV , 2010a):

$$\{\gamma_{sc} * \gamma_m\}\left\{\left(\frac{|M_d|}{M_k} * \sqrt{1-\left(\frac{p_{ld}-p_e}{p_b(t_2)}\right)^2}\right)+\left(\frac{T_{ed}}{T_k}\right)^2\right\}+\left(\frac{p_{ld}-p_e}{p_b(t_2)}\right)^2 \leq 1 \qquad Eq. 3.3$$

Considering that:

$M_d = \gamma_F M_F + \gamma_E M_E + \gamma_A M_A$; Design bending moment

$T_{ed} = \gamma_F T_{eF} + \gamma_E T_{eE} + \gamma_A T_{eA}$; Design effective tension

$\gamma_{F,E,A}$; Load effect factors for Functional/Environmental/Accidental

$M_{F,E,A}$; Bending moment from Functional/Environmental/Accidental loads

$T_{eF,eE/eA}$; Effective tension from Functional/Environmental/Accidental loads

$T_k = f_y * \alpha_c * \pi * (D - t_2)^2 * t_2$; Plastic axial force resistance

$M_k = f_y * \alpha_c * (D - t_2)^2 * t_2$; Plastic bending moment resistance

D External diameter

f_y Material yield strength

t_2 Nominal Wall Thickness

T_k Plastic axial force resistance

α_c Flow stress parameter accounting for strain hardening

$p_b(t_2) = \frac{2}{\sqrt{3}} * \frac{2*t_2}{D-t_2} min\left(f_y; \frac{f_u}{1.15}\right)$; Burst resistance

$t_2 \quad = t_{nom} - t_{corr}$

t_{nom} Specified or nominal pipe wall thickness

t_{corr} Corrosion/Wear/Erosion allowance

f_u Ultimate yield strength

p_{ld} Local internal design pressure

p_e Local external pressure

For the case of combined loading with the riser is subjected to effective tension, bending moment, net over pressure, it then the following equation must be applied:

$$\{\gamma_{sc} * \gamma_m\}^2 \left\{\frac{|M_d|}{M_k} + \left[\frac{T_{ed}}{T_k}\right]^2\right\} + \{\gamma_{sc} * \gamma_m\}^2 \left(\frac{p_{ld} - p_e}{p_b(t_2)}\right)^2 \leq 1 \qquad Eq. 3.4$$

With; $p_c(t_2)$ as the Hoop buckling capacity

3.5 Serviceability Limit State SLS

Serviceable limit state involves the disruption of use of the riser as intended for the normal operation. FMEA and HAZOP are used to identify limits and to determine the consequences of exceeding the limitations.

According to DNV 2010a, riser must not be subjected to excessive ovalization and it should be documented. Operating procedures shall mention all limitations and the assumptions. Serviceability Limit State regarding to global riser behavior are deflection, rotation, displacement and ovalization of the riser. Excessive ovalization of the pipe is not permitted and limitations must be documented, like for example that the total out-of-roundness is limited to 3% as stated in the following equation:

$$f_0 = \frac{D_{max} - D_{min}}{D_0} \leq 0.03 \qquad Eq. 3.5$$

Some examples of SLS were mentioned in chapter 3.2 of this document and in section 5 of DNV-OS-F201, acceptance criteria can consider limitations during riser installation to avoid riser interference.

3.6 Accidental Limit State

The Accidental Limit State (ALS) is a limit state that consider events or accidental loads, for instance, involves damage or failure due to unusual, accidental, or unplanned loading conditions such as: Dropped objects (impact lading), Incidental overpressure, explosion and fire, severe earthquakes or environments.

According to DNV 2010c, Accidental Limit State design checks apply resistance against direct accidental load, which are commonly discrete events with a value of less than 10^{-2} for the frequency of accordance in a year, checks also apply consequences and ultimate resistance evaluation due to exceedence of a serviceable limit state brought in to delimit operational limitations as well as consider post-accidental resistance against environmental loads when required.

3.7 Fatigue Limit State

For this limit state, a safety margin have to be defined adequately for the riser to face fatigue inside the life cycle of the system. According to DNV 2010a, all cyclic loading that the riser is exposed throughout its service life, should have a value and equivalent number of cycles sufficiently large to cause fatigue damage effects. Likewise, temporary stages such as towing, transportation and installation should be considered. Table 3.6 mention the design fatigue factor according to the standard (DNV, 2010a).

Table 3. 6: DNV-OS-F201 Design Fatigue Factors

Safety classes		
High	Medium	Low
10	6	3

The fatigue assessment method lists two kinds of categories:

- Methods that implement S-N Curves

$$D_{fat} * DFF \leq 1 \qquad \textit{Eq. 3.6}$$

With:

D_{fat} Accumulated fatigue damage

DFF Design fatigue factor according to Table 3.6.

- Methods that implement fatigue crack propagation.

$$\frac{N_{tot}}{N_{cg}} * DFF \leq 1 \qquad \textit{Eq. 3.7}$$

DFF Design Fatigue Factor as shown in Table 3.6.

N_{cg} Number of stress cycles needed to increase the effect from initial to the critical size

N_{tot} Total number of applied stress cycles while in inspection or service.

Chapter 4. Installation and Fabrication of Risers

4.1 Riser installation and construction methods

The three main pipe laying methods applied in the offshore industry are:

- S-Lay
- Reeling
- J-Lay

The principles in which these methods work rely on the allowable bending stresses, the allowable axial stresses and the prevention of kicking.

The most important subsea pipeline installation companies are Saipem, Subsea 7, TechnipFMC and Allseas Group. Below is a description of the most common methods of pipe installation.

4.1.1 S-Lay

The main characteristic of this pipelay method of installation is that the pipeline takes a "S" shape, Figure 4.1. The method takes its name from this shape of the suspended pipe. This is the most common adopted technique for marine pipeline installation. It has been originally developed to lay pipe in a shallow water near shore in Gulf of Mexico in the 1940s and 1950s.

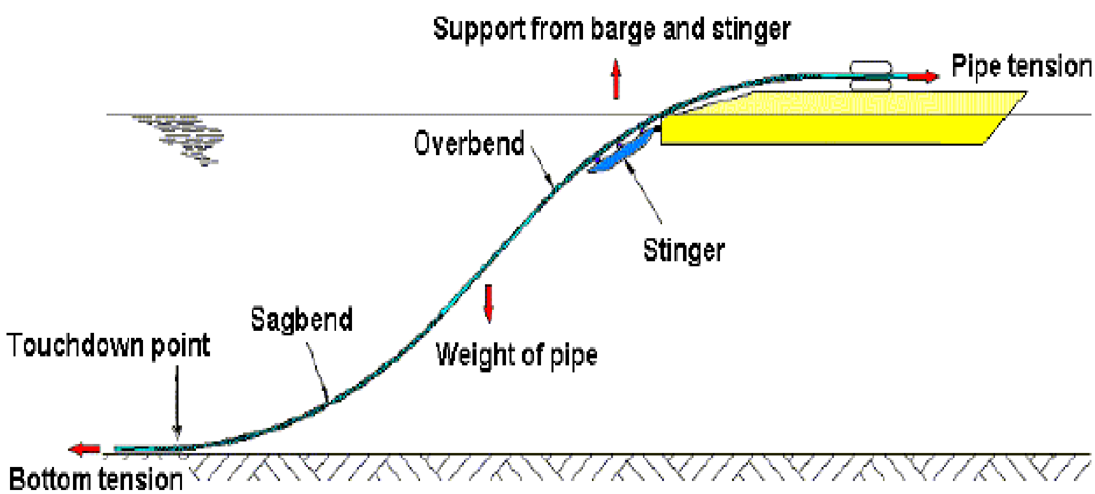


Figure 4. 1: S-lay installation method.
(Karunakaran, 2017)

For this method of installation, the pipe must be tensioned to hold its shape. This is achieved by tensioners, equipment consisting of rolling belt with rubber pads that are hydraulic operated to press the pipe and keep the pipe sagbend in the acceptable range. Due to its weight, the pipeline is curved near to seabed, creating a sagbend. It is one of the critical sections of pipeline.

Pipes of 12m-24m are built and coated onshore, these pipes then transported to the pipelaying vessel. The construction is based on a moored or dynamically positioned barge. The lengths of the pipe are lined up the upper end of the ramp and passed through a series of welding stations as the barge moves forward (Tewolde, 2017). The tensioners apply a force to the pipe near the stern end of the ramp. The upper curvature of pipe on the stinger is called over bend. The pipe leaves the barge at the stern and passes over the rollers supported by stinger structure. The pipe loses contact with the stinger and continues through the water as a long-suspended span, the sagbend, and then reaches seabed tangentially at the touchdown point TDP. The shape of the pipe in the sagbend is handled by the resultant between the applied tension and submerged weight of the hanging pipeline.

The advantages of the ‘S’ lay installation technique are the following:

- No limitation on the length and diameter of the pipe that it can accommodates.
- The technique is suitable for routing and reducing spans.
- Minimal modification are needed to be implemented to its system to suit different diameters during pipeline installation.
- Once the barge is mobilized, it can work without restrictions with minimal support from inland base.
- Suitable for installation in shallow and intermediates water.

Figure 4. 2: S-lay installation vessel Audacia, Allseas Group – Length of 225m. (All seas group, 2015)

Some of the drawbacks of the S lay method are:

- The shape and size of the stinger is proportional to the water depth, can reach 100m long.
- Top tension capacity limited installation in large water depths.
- Large hydrodynamic appeared on the stinger and pipeline as the vessel moves.

Unmanageable movement of the pipelay vessel, loss of tension, excessive bending, collapse or local buckling can appear. Figure 4.3 present the local buckling propagation in detail.

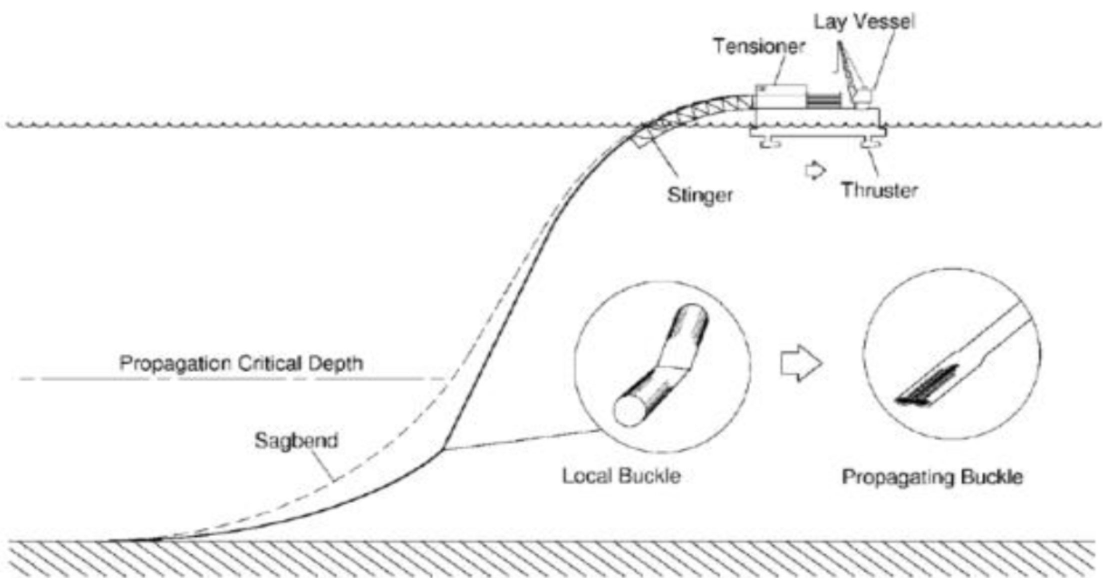


Figure 4. 3: Propagation of buckle from a local buckle in the S-lay installation method. (Kyriakides & Corona, 2007)

4.1.2 J-Lay

Pipes are installed in "J" shape and welded at J lay vertical tower while having support, leaving the vessel almost at vertical position. This technique is a highly efficient installation method for small diameter risers or pipelines. This allows the elimination of the overbend section compare to the S-Lay method. J-lay technique schematic is shown in Figure 4.4. J-lay method can install pipes up to 24" and have many companies offering the service worldwide. A J-lay pipelaying vessel reduces the stinger requirements, using the same tower in which the pipe is being welded to support the pipe for laying purposes. The angle of pipe laying from the vessel is in the range of 0 to 15 degrees, with this, the stinger used in J-lay must change the angle of pipeline with respect to vertical orientation. Thanks of having one welding and one inspection section in J-Lay tower, long sections of onshore welded pipes are used in laying process to increase the efficiency and reduce installation time.

According to the Wartsila encyclopedia of Marine Technology, 2019; pipe stalks with a length up to six (6) joints are constructed (upended and welded) to the seagoing pipe near vertical ramp. The ramp angle is selected in a way that it is in line with the pipe catenary to the seabed. (Wartsila Encyclopedia of Marine Technology, 2016)

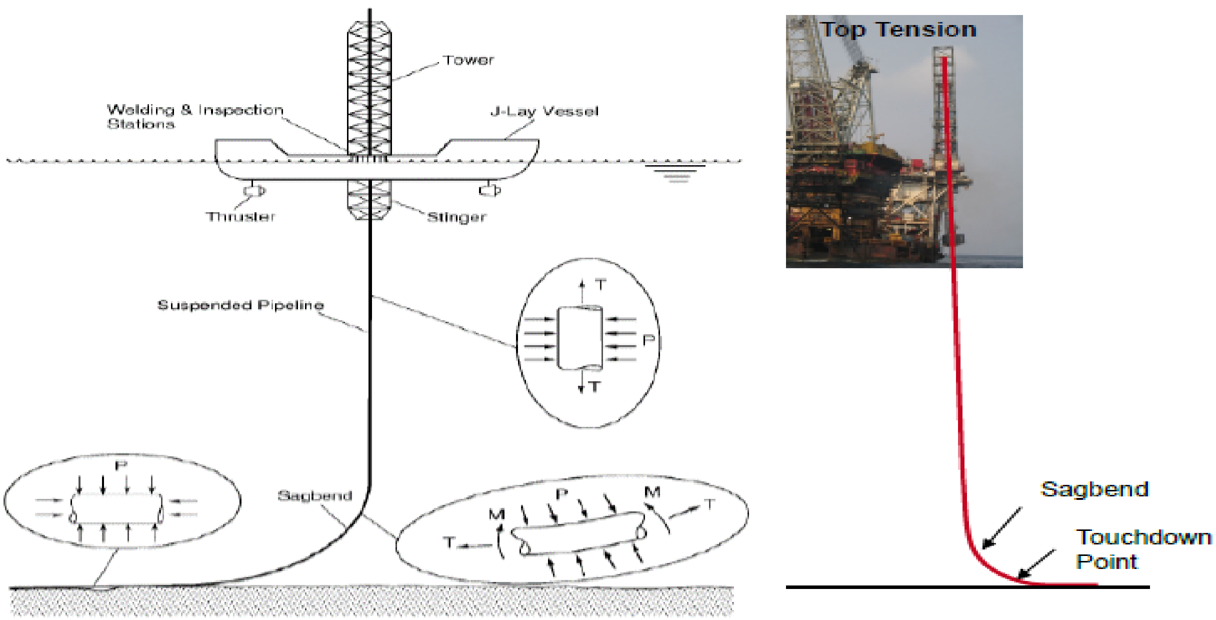


Figure 4. 4: J lay Installation schematics
(Karunakaran, 2017) (Kyriakides & Corona, 2007)

The “J” method has a slow day rate of pipe laying comparing with S-lay. Likewise, the long heavy vertical tower causes the instability issues to the vessel. However, the J-lay method is considered favorable as bending stresses are low and forces required for station keeping of the vessel are within acceptable range. This method is not good for shallow water. One of the largest J-Lay vessels is Saipem 7000 shown in Figure 4.5.

Figure 4. 5: Saipem 7000. Semi-submersible crane and pipe laying vessel.
(Saipem, 2010)

4.1.3 Reeled lay

In the reeled lay method, pipes are reeled on to a big reel and laid from the reel offshore. Reeling is a very efficient method for the installation of pipelines and risers. This method is very efficient installation from for small diameter pipelines, also reeling is also suitable for cables, umbilicals, flexible and rigid pipes up to 18” in diameter. Smaller vessels are used, allowing faster mobility.

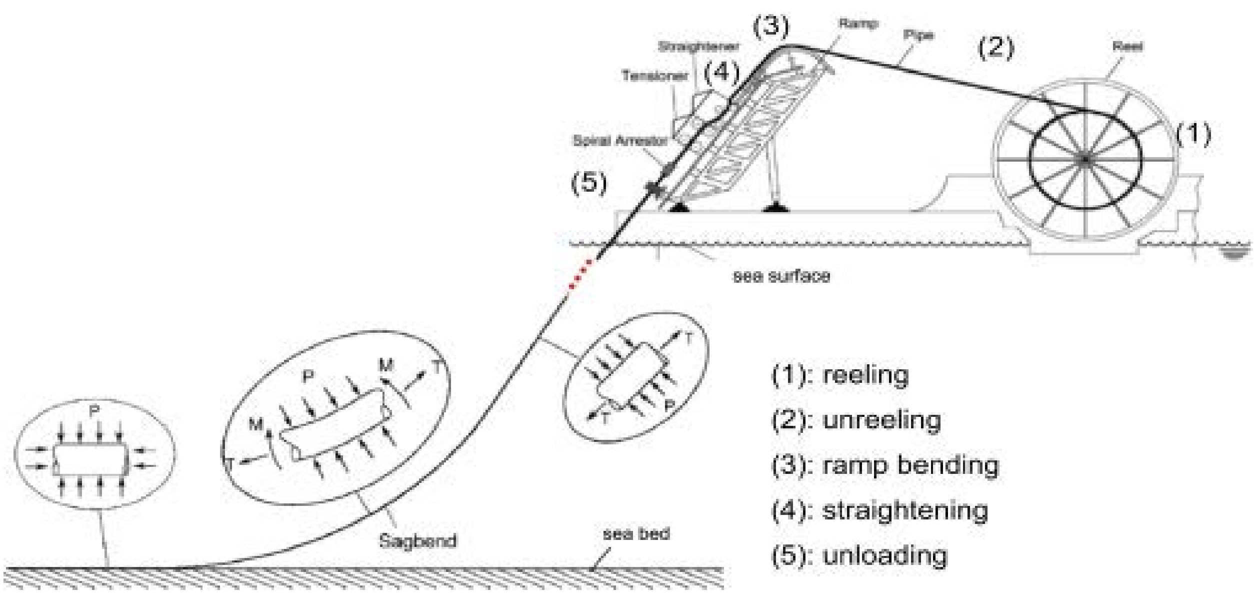


Figure 4. 6: Schematic for reeling installation.
(Karamanos, Varelis, & Chatzopoulou, 2016)

The pipeline or riser construction process such as assembly, welding, inspection and coating are made onshore at a spool base, where pipeline is welded and then reeled on a big diameter reel drum fixed on the reel-lay vessel, as shown in the Figure 4.6. The long strings of pipeline fabricated are called “stocks”. The vessel takes the stocks to the installation site offshore and the unspooling of pipes starts. In Norway, both Technip and Subsea7 have reel lay capabilities.

The pipeline is unreeled while the vessel moves forward with attached straighter and tensioners (Figure 4.6). The reeling and unreeling process of pipe induce large strains in the pipe in range of 2%-3%, which needs to be mechanically straightened out during unreeling. Mechanical properties like wall thickness must be design carefully to avoid local buckling. The current limit of this method is 18” of external diameter, thus wall thickness can be dictated by reeling criteria rather than operational criteria, like for example burst, collapse) (Karunakaran, 2017). The reeling of pipelines and risers has advantages on installation time and general cost benefits.

This method is suitable for plastic lined pipelines in water injection and corrosion resistant materials. Also, this technique is suitable for various coating such as Fusion Bonded Epoxy (FBE) and solid polypropylene; however, it is not appropriate for concrete coating. (Tewolde, 2017)

Reel-lay vessels resemble more to the J-lay type of installation because of the use of a tower, even though the vessels may have horizontal reel and pipe is laid into the sea overs stinger like S-Lay. The reel drum is permanently installed on the vessel and can be recharged with new pipes. Figure 4.7 shows two pipe-lay vessels, the Seven Navica reel Ship, and the Seven Ocean new reel ship.

Reeling induces plastic deformation in a pipe (plastic strains). But steel pipe reeling is possible because the linepipe and the pipeline welds are ductile, the linepipe steel strain hardens and the reeling is displacement controlled. Figure 4.8, shows the spooling operation, showing the pipeline goes through elastic deformation and plastic deformation in the reel.

Figure 4. 7: Seven Navica Reel ship and Seven Oceans New Reel ship, subsea7 (Karunakaran, 2017) (Subsea7, 2015)

Some of the issues with the reel lay are (Karunakaran, 2017):

- Pipe section stiffness may differ between adjacent joints, then possibly causing discontinuities and strain concentrations.
- Strain concentrations may cause local buckle close to the pipe joints.
- Section stiffness changes due to variation in geometric (wall thickness changes) and in material properties such as yield strength.

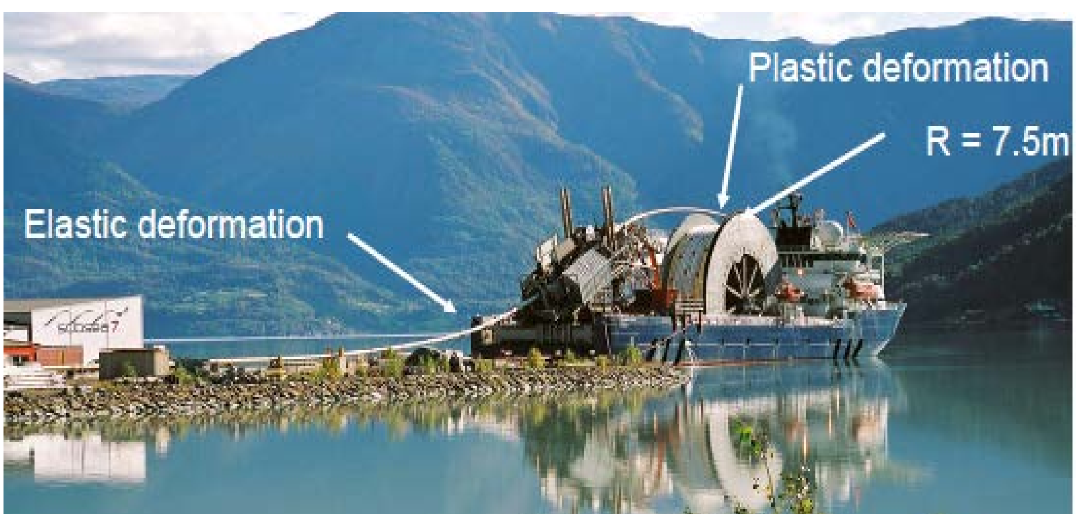


Figure 4. 8: Spooling operation
(Karunakaran, 2017)

Chapter 5. Residual Curvature Method

5.1 Residual Curvature Method - RCM

This method for controlling lateral buckling in subsea pipelines was developed and patented by Statoil (USA Patent No. US 6,910,380 B2: Method for Pipelaying from a Coil to the Sea Bed, Controlling Thermal Expansion, 2005). According to this patent, the idea is to create intermittent un-straightened or residual curvature sections in the pipeline during the reel-lay installation; therefore, the buckle may be started in these places once the pipeline enter in operation. (Endal, Ness, Verley, Holthe, & Remseth, 1995). The controlled thermal expansion will be started and handled in these buckle sites at uniform intervals. The method of residual curvature RCM is valid for pipelines which are installed by reel-lay. The residual curvatures are generated at the straightener of the reel lay vessel during the pipelay as shown in Figure 5.1.

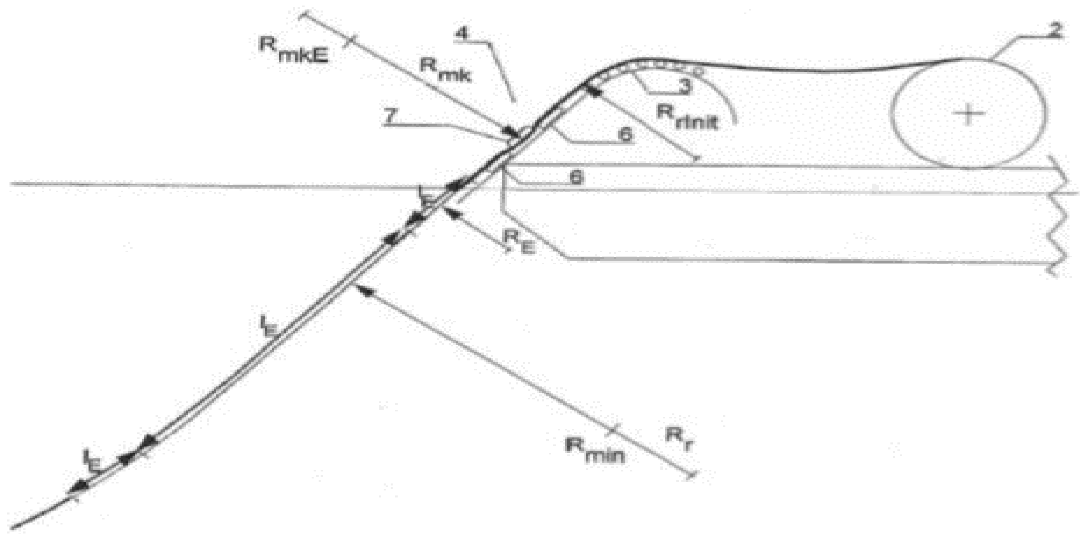


Figure 5. 1: Straightener & residual curvatures during reel-lay installation.
(USA Patent No. US 6,910,380 B2: Method for Pipelaying from a Coil to the Sea Bed, Controlling Thermal Expansion, 2005)

On the tower of the reel-lay vessel, the straightening creates imperfection in the pipeline by generating residual strain at pre-designed locations along the pipeline. This is attained by adjusting the corresponding parts in the straightener. A normal configuration of the residual curvature is to generate a residual strain of 0.15% - 0.25% over a predefined curvature length that can be 40m, 70m or 100 meters length for each kilometer during the reel-lay installation as illustrated in Figure 5.2.

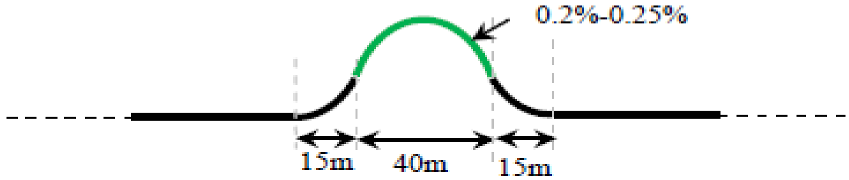


Figure 5. 2: Residual curvature section
(Roy, Rao, Charnaux, Ragupathy, & Sriskandarajah, 2014)

Surveys and analysis after installation under operational conditions corroborate that the application of the un-straightened section with the RCM method is an appropriate and effective technique for controlling lateral buckling of subsea pipelines due to that the cost of its implementation is negligible, does not require any additional control buckling measure to guarantee its use within the acceptable criteria. Moreover, the RCM has shown to be a trustful, robust and cost-effective technique comparing with the conventionally used buckle initiation methods.

Figure 5. 3: Straightener equipment in a reel-lay vessel.
(Wartsila Encyclopedia of Marine Technology, 2016)

A finite Element mode was developed in Subsea7 to simulate reeling and straightened onboard the Seven Oceans; this simulation showed that an under-straightening configuration of 0.2% to 0.25% of residual strain was an optimum value. (Roy, Rao, Charnaux, Ragupathy, & Sriskandarajah, 2014). Likewise, in the thesis "Pipelay with Residual Curvature" (Tewolde, 2017), made a study and validation on the findings in the paper "Reel-lay Method to Control Global Buckling" (Endal, Giske, Moen, & Sande, 2014) for the tendency of the pipeline to roll and bend due to the un-straightened or residual curvature sections added on the reel vessel can be calculated by an energy approach.

The un-straightened sections are introduced in the vertical plane on the reel-lay vessel. The simplified energy approach is applied to find the tendency of the pipeline rotation value when the RCM is implemented at intervals with the help of the straightener.

The total work done from the vessel to the touchdown point is the combination of the bending and roll work made in the pipeline. The roll angle (ϕ_0) at TDP can be found by the minimization of the total rotational and bending work done in the suspended section of the pipeline (Endal, Giske, Moen, & Sande, 2014). This is important for the correct landing of the section with residual curvature in the seabed according to what is require by its topography, may be in a horizontal plane or certain angle.

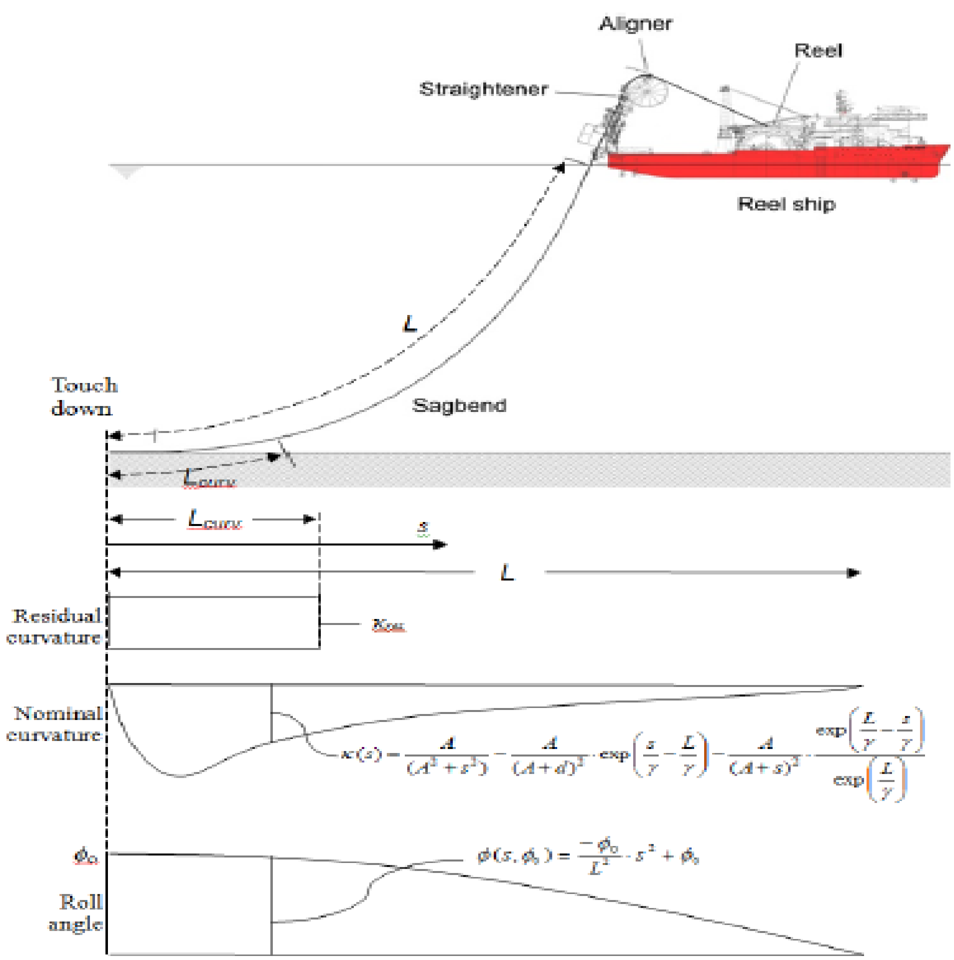


Figure 5. 4 Simplified analytical approach of pipe roll in reeling
(Endal, Giske, Moen, & Sande, 2014)

Figure 5.4 illustrates the shape of the hanging pipeline together with the roll angle and nominal curvature as well as the equations used in the simplified analytical approach to estimate the pipeline roll. This is worth mentioning as may be applied for calculations in free hanging steel catenary riser installation if Residual Curvature Method is applied.

5.2 Bending moment, curvature and residual strain

5.2.1 Bending moment and curvature

Pipelines and risers are exposed to bending moments during installation. For S-lay technique, the pipe suffer bending at the overbend as well as in the sagbend near to seabed. In the reel-lay method, the pipe experience plastic bending once reeled and later straightened by reverse plastic bending, and at the sagbend. Likewise, while in operation, pipeline bend in the seabed due to its topography and irregularities. Figure 5.4 shows the relation between curvature and bending moment in a pipeline subjected to bending forces until reaching the plastic area.

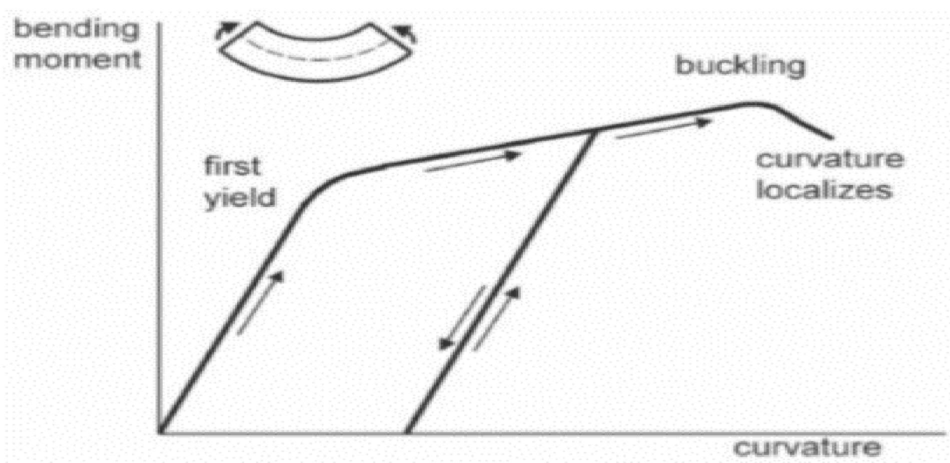


Figure 5. 5: Relation between Bending Moment and curvature. Buckling.
(Palmer & King, 2004)

The pipe bends elastically with small curvature, but after certain curvature applied above the yield curvature, the pipe bend plastically. The relationship between the moment and the curvature is called flexural rigidity F.

According to Tewolde, 2017; “once the curvature has growth, the bending moment continues to be amplified although gradually at a rate controlled by the interaction between strain-hardening that tends to increase the bending moment, and the ovalization that tends to reduce the bending moment". Then, if at that phase the curvature is decreased, the bending moment reduces in a linear way, and when the moment becomes null, there will be a residual curvature RC. If the curvature increases continuously, the bending action will become unstable, and the pipe begin to wrinkle on the compressive section. In this location, the bending moment decreases, and a buckle is generated. The curvature becomes ununiformed, then setting up on it a buckle producing a large curve. (Palmer & King, 2004)

5.2.2 Residual strain and curvature

Once there is residual curvature, it is relevant to measure this in terms of residual strain, which is the measure for its application. Figure 5.5 illustrates the relation between the residual strain and the curvature.

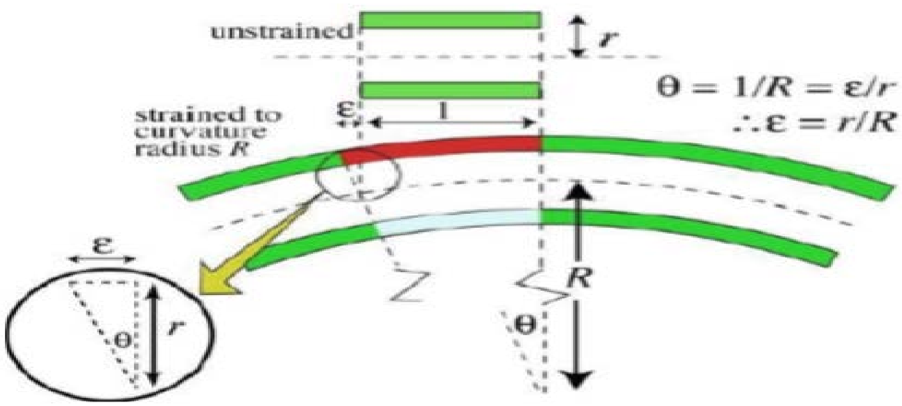


Figure 5. 6: Strain-Curvature relationship for a pipeline.
(University of Cambridge, 2004)

With the radius of curvature R:

$\tan\theta = \frac{1}{R}$ With a θ of small value, then it becomes: $\tan\theta = \theta$

We have that; $\theta = \frac{1}{R}$ Curvature

Likewise, by similar triangles:

$\tan\theta = \frac{\varepsilon}{r}$ With a θ of small value , $\tan\theta = \theta$

Then, $\theta = \frac{\varepsilon}{r}$

Thus, $\frac{1}{R} = \frac{\varepsilon}{r}$ and rearranging we have: $\varepsilon = \frac{r}{R}$ *Eq.4.2.2.a*

Using equation 3.2.2.a, strain and curvature can be defined as:

Strain; $\varepsilon = \frac{r}{R} = \frac{d}{2R}$ *Eq.4.2.2.b*

Curvature; $\theta = \kappa = \frac{1}{R}$ *Eq.4.2.2.*c

Therefore, the relationship of the amount of curvature and the value of residual strain is (University of Cambridge, 2004):

$\varepsilon = \frac{r}{R}$ = r*k *Eq.4.2.2.d*

Where,
- R Radius of curvature
- ε Strain
- κ Curvature
- d Diameter of pipeline (OD= Outer diameter)
- r External Radius of pipeline

Table 5.1 presents the calculation of residual strains and the residual radii for the single section. The two diameters to be shown as an example are 10" ID and 14" ID.

For example, for ID10" riser and residual strain of 0.15%.

$$\theta = \frac{\varepsilon}{\left(\frac{d}{2}\right)} = \frac{0.0015}{\left(\frac{0.332}{2}\right)} = 0.00903 = \frac{1}{R}$$

$$R = 110.67m$$

Table 5. 1 Residual strains to radius of curvature

Residual Strain	**Radius of residual curvature (m)**	
	ID 10" = 0.254m OD = 0.332m Wall thickness = 0.039m	ID 14" = 0.3556m OD = 0.4056m Wall thickness= 0.022m
0.15%	110.67m	135.2m
0.20%	83m	101.4m
0.25%	66.4m	81m

5.3 Residual curvature application in Reel-lay

The application of the residual curvature can be summarized as follow:

- Reeling of pipeline
- Unreeling
- Aligning
- Straightening (Applying the residual curvature when needed)
- Lowering the pipeline

The reeled lay installation method of subsea pipelines includes the reeling as well as posterior unreeling. While this procedure is performed, the pipeline goes through elastic and plastic deformations and have accumulated strains and bending cycles.

The Figure 5.6 illustrates the reeling of the pipeline made in a reel-lay ship at the spool location. For this reeling process, the pipeline under tension goes to the aligner on an inclined ramp that has a slope which is specify by the angle (θ) of the spooling tower measured in relation with the horizontal plane.

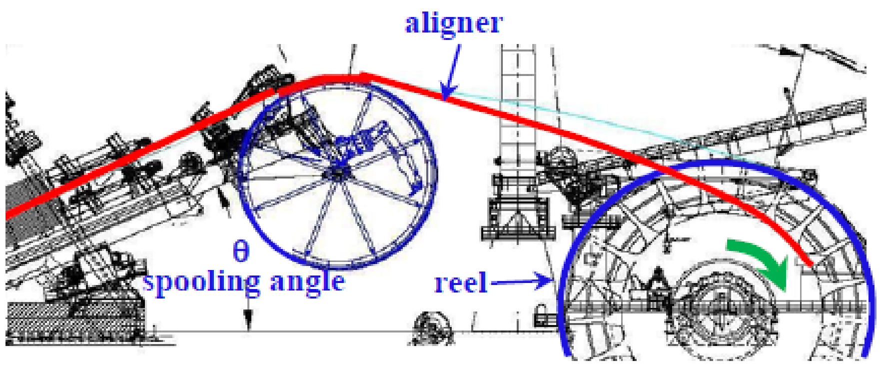


Figure 5. 7: Pipeline Reeling
(Roy, Rao, Charnaux, Ragupathy, & Sriskandarajah, 2014)

When the reel-lay vessel is on the location for the installation, the unreeling of pipeline is achieved in a reverse process comparing with the reeling process. During the unreeling, the tower angle is increased according to the designed lay-angle as shown in the Figure 5.7. After that, the pipe is wound off from the reel, passes though the aligner to continue throughout the straightener.

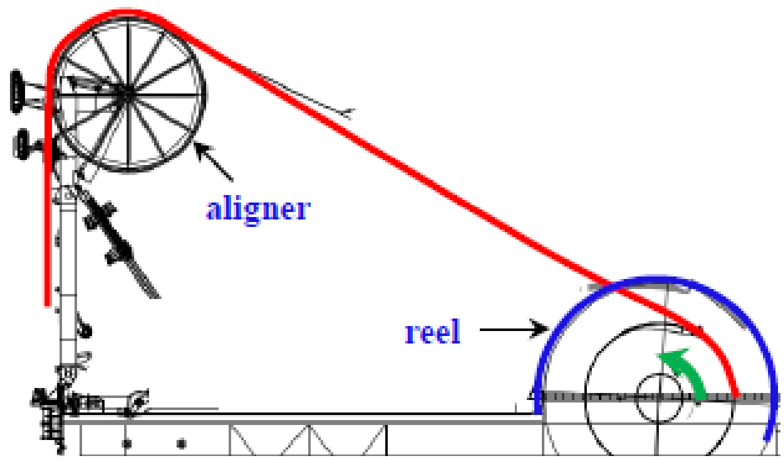


Figure 5. 8: Unreeling the pipe.
(Roy, Rao, Charnaux, Ragupathy, & Sriskandarajah, 2014)

A straight pipe, following the code DNV-OS-F101, is a pipe for which the Out-Of-Straightness (OSS) satisfies the following requirement (DNV, 2007):

$$OOS < 0.15\%\ L \qquad Eq.5.3.a$$

Where, OOS = Out-of-straightness

L = Actual length of pipeline

This means that for example for a 6m pipe, the joint have to be over 9mm, this can be seen in the Figure 5.8. Other way to interpret this is that the radius of curvature should be over 500m (0.002 m^{-1}).

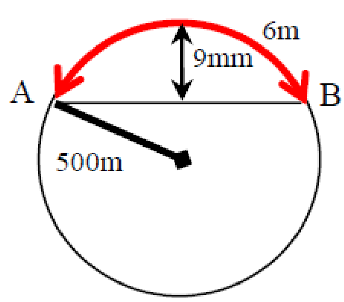


Figure 5. 9: DNV-OS-F101 criterion for a straight pipe.
(DNV, 2007)

The reel-lay vessel has the straightener install in the tower; its function is to straighten the pipe after it passes through the aligner from the reel drum. Figure 5.9 shows the straightener equipment. Once the pipe leaves the aligner, a reverse bent to the curvature is applied with the help of the upper track.

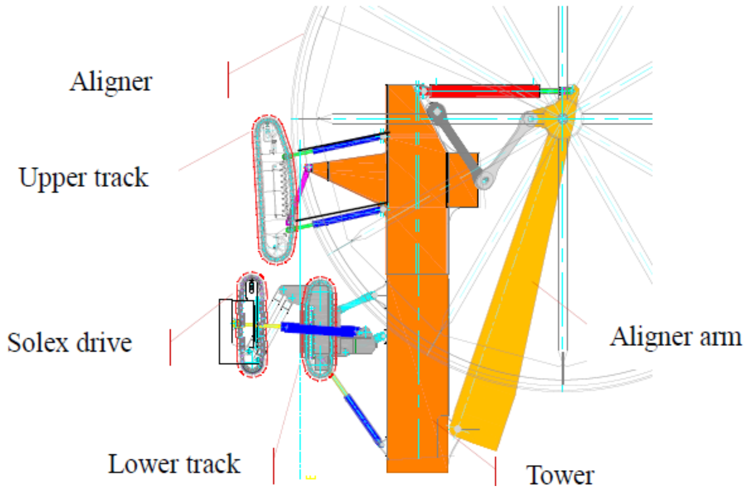


Figure 5. 10: Straightening equipment
(Roy, Rao, Charnaux, Ragupathy, & Sriskandarajah, 2014)

Citing Tewolde, 2017; "The straightener has three main components: Upper track, Sole drive and Lower track" as shown in the Figure 5.10. After passing through the aligner, it is inversely bent to the target curvature or straightness given by the upper track. The pipeline or riser enters the tensioner aligned by the lower track to avoid any misalignment from occurring in the point of entry.

A straight or under-straight pipe is attained by adjusting the orientation and position of the upper track that can modify the level of reserve curvature. The succession of three hydraulic cylinders (top, bottom and positioning cylinders) are installed to handle the upper track. (Tewolde, 2017)

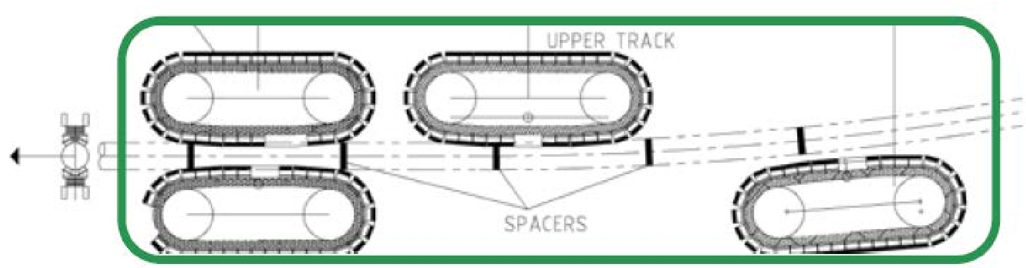
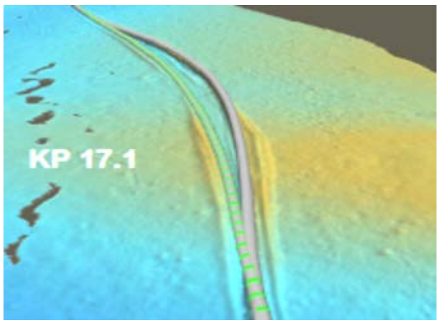


Figure 5. 11: Straightener in detail tracks.
(Endal, Giske, Moen, & Sande, 2014)

5.4 Applications of local residual curvature

As mentioned, the Skuld Project was the first to applied residual curvature method in pipeline. The results are summary as follow:

- No other measures required to control thermal buckling
- Vessel time 10-20 mins per location
- A validation was run by an operational survey in December 2014. Conclusion: Lateral deflection was controlled at every local residual curvature location.



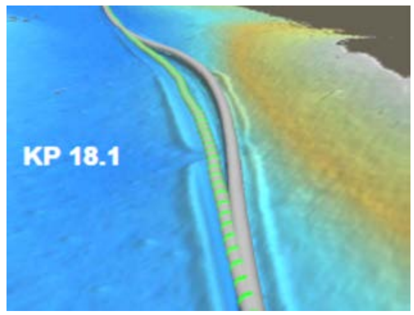


Figure 5. 12: Initial location of the pipeline (With green stripes) and location at the posterior inspection.
(Endal, Giske, Moen, & Sande, Reel-Lay Method to Control Global Pipeline Buckling Under Operating Loads, 2014)

The posterior inspection was made under operating conditions and confirmed that the method was effective and suitable for controlling lateral buckling and that the buckles appear at the under-straightened sections. Each section generated the lateral buckling as expected.

This method could potentially be applied for the part of the riser laying on the sea bottom to increase active resistance (riser-soil interaction) and to adjust it to the topography of the seabed as will be mentioned next.

Besides using the residual curvature methods for controlling global lateral buckling, the method of residual curvature can potentially be applied in the following cases (Endal & Nystrøm, 2015):

- Enable direct tie-in of pipelines or risers as shown in Figure 5.12.

- Installation of pipeline or risers shaping it to seabed topography. Figure 35. (Endal , Nystrøm, & Lyngsaunet, 2015)

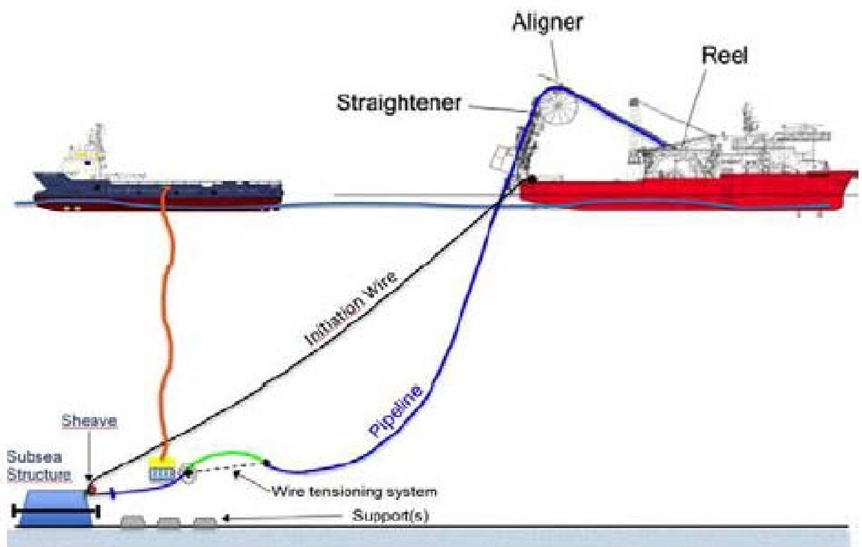


Figure 5. 13: End Direct Tie-in using Residual Curvature Method.
(Nystrøm, Endal , & Lyngsauner, 2015)

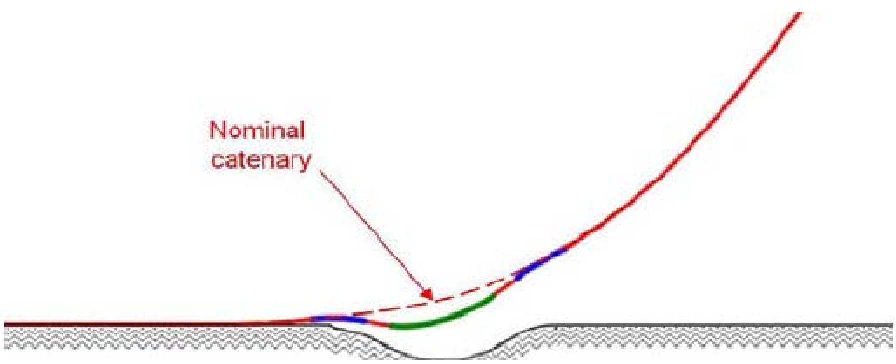


Figure 5. 14: Pipeline configurations during installation with residual curvature and nominal catenary.
(Endal , Nystrøm, & Lyngsaunet, 2015)

- Eliminate straightening trials for reel-laid pipelines or risers. (Endal & Nystrøm, 2015)
- Potential reduction of fatigue and stress loads for SCR (Endal & Nystrøm, 2015):

This thesis project is studying this potential application of the Residual Curvature Method.

Chapter 6. Design Basis and Methodology

6.1 Introduction

The riser properties, methodology and data which are going to be used for the study and analysis of the implementation of residual curvature and the resulted riser configuration are specify here. It has been chosen that the free hanging steel catenary riser SCR concept will be analyzed comparing it with the configuration of SCR with residual curvature method applied, from now on called RCSCR. The goal of this thesis work is to investigate the riser in relation with its ability to handle motions in the selected floating unit (semi-submersible.)

The design information and properties are fundamental for the modeling, analysis as well as validation of the riser concept performance for deepwater under real conditions. The riser concept with residual curvature will be proposed and designed to satisfy strength as well as fatigue requirements. The analysis is developed using the finite element method FEM with a non-linear time domain analysis model. The software for the study of the model used is OrcaFlex (Version 10.1b), which is a highly reliable software manufactured by Orcina (Orcina, 2016). OrcaFlex is a software package for the dynamic analysis of offshore structures, well known due to its extensiveness of technical capability and user friendliness. A general description of the software is written in the Appendix B.

6.2 Global Analysis

The results of global response analysis are classified following DNV, 2010a:

- Global riser position: Distance to other structures Co-ordinates, position of TDP on the seafloor.
- Calculations of cross-sectional forces: Effective tension, bending moments, torsional moment.
- Support forces at termination to rigid structures: Resulting force and moments.
- Global riser deflections: Curvature, elongation, angular orientation. (Gemilang, 2015)

6.3 Environmental Data

6.3.1 Water Depth

The water depth of 1500m (4921 feet) was chosen as it is an average depth for offshore field developments in GoM. Likewise, a constant seawater density of 1025 kg/m3 with a temperature of 10°C. According to Bai et al., the water depth of 1500m is considered as deep water.

6.3.2 Current

The current data used for this work consider a typical current profile in the Gulf of Mexico. The current profile is mentioned is relation to the current velocities over water depth that has its maximum at the sea surface (0 meter) and the minimum value near the seabed (3 m above the seabed).

According to DNV GL, 2015; the sea surface current speed with a 10-year return period should commonly be used. Table 6.1 shows the values for the current speed. This is based on the marginal distribution of current speeds in the GoM (DNV GL, 2015).

Table 6. 1: 10-year sea surface current speeds at GoM (DNV GL, 2015)

Gulf of Mexico	
Hurricane	1.8 m/s
Winter Storm	1.08 m/s
Loop Current -100 year	2.37 m/s

In the extreme response analysis, the current profile approximation for 10-year return period in Gulf of Mexico is taken into account. Table 6.2 and Figure 6.2 show the values for the current and depth. These values follow the results obtained from a current profile from the study made by the Costal Marine Institute in USA. (Costal Marine Institute, 2008)

Table 6. 2: 10-year Current Profile in GoM for Hurricane condition.

Water Depth	10-year current
m	m/s
0	1.8
-50	1.5
-100	1.3
-200	1.1
-300	1
-400	0.9
-500	0.8
-600	0.7
-800	0.6
-1000	0.5
-1200	0.45
3 m above the seabed	0.4

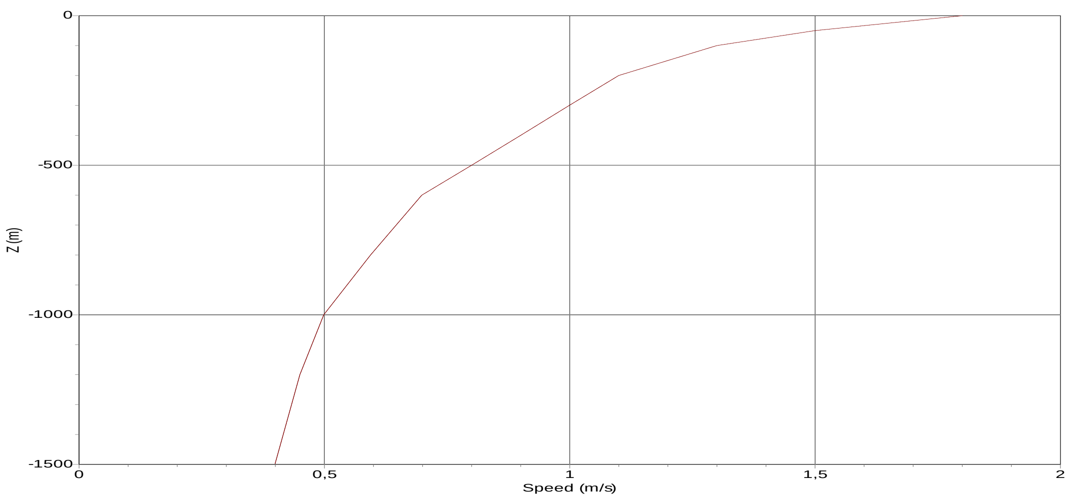


Figure 6. 1: Illustration for typical current profile in GoM (Costal Marine Institute, 2008)

6.3.3 Waves

The intention of this thesis is to investigate performance and limitations of the conventional Steel Catenary Riser with the application of residual curvature in terms of the ability to handle large floater motion, therefore, several sea states are applied in order to generate different responses for the floater heave motions. The load cases include current as well as wave data. For wave modelling, different data have been chosen for the study. The extreme sea state is modelled by irregular waves, implementing JONSWAP spectrum that is used to characterize the North Sea conditions; however, as explained before it is a good model to simulate the heavy wind generated sea during a winter storm or a hurricane that occurred in the Gulf of Mexico.

The JONSWAP Spectrum is defined as used by the software OrcaFlex (Orcina, 2016):

$$S(f) = \frac{\alpha g^2}{16\pi^4} f^{-5} * \; exp\left[-\frac{5}{4}\left(\frac{f}{f_m}\right)^{-4}\right]\gamma^b$$

Where

$$b = exp\left[-\frac{1}{2\sigma^2}\left(\frac{f}{f_m} - 1\right)^2\right]$$

$$\sigma = \begin{cases} \sigma_1 & for\ f \le f_m \\ \sigma_2 & for\ f > f_m \end{cases}$$

With $\boldsymbol{g}$**,** as acceleration of gravity and the remaining parameters γ, α, σ1 and σ2 being data items

Typical sea states at GoM with a 100-years return period are shown in Table 6.3. Each sea state of 3-hour duration is characterized by maximum significant wave height (Hs) and wave period (Tp):

Table 6. 3: 100 year 3h-sea state at GoM for different conditions.
DNV-OS-E301 *pg23* (DNV GL, 2015)

Gulf of Mexico Sea state conditions and parameters		
Winter storm	Hs	7.3 m
	Tp	10.8-12.8 m
Hurricane	Hs	15.8 m
	Tp	13.9 – 16.9 s

The JONSWAP spectrum need information on the significant wave height (Hs), spectral peak period (Tp) and peak shape parameter (γ) to carry out the simulation of irregular wave. It is important to remember that the peak shape parameter depend of the significant wave height and the peak period. Peak shape parameter (γ) is calculated with the following equations (DNV GL, 2015):

$$\gamma_p = 5 \qquad for \quad \frac{T_P}{\sqrt{H_S}} \leq 3.6$$

$$\gamma_p = e^{5.75-1.15\frac{T_P}{\sqrt{H_S}}} \qquad for \qquad 3.6 \leq \frac{T_P}{\sqrt{H_S}} \leq 5$$

$$\gamma_p = 1.0 \qquad for \;\; 5 \leq \frac{T_P}{\sqrt{H_S}}$$

The significant wave height (Hs) is ranging from 4 m to 15.8 m considering their respective peak periods. The idea is having an approximation of 3-hour sea-states generated in different events including 100-years 3-hour winter storm and 100-years 3-hour hurricane. With this, it will be possible to obtained different results for the downward velocities at the hang-off point.

Table 6. 4: Wave Data

Sea State condition	**Wave Characteristics**	**Hs (m)**	**Tp (s)**	**γ**
Reference Storm	Load Case 1	4	16	1
*Winter Storm**	Load Case 2	7,3	12,8	1,352
Reference Storm	Load Case 3	8	16	1
Reference Storm	Load Case 4	9	16	1
Reference Storm	Load Case 5	10	16	1
Reference Storm	Load Case 6	11	16	1,224
*Hurricane**	Load Case 7	15,8	16,9	2,365

* DNVGL-OS-E301 Typical 100-year Hs and Tp for GoM under Winter Storm or Hurricane Conditions

The Sea State conditions 1, 3, 4, 5 and 6 indicated in Table 6.4 as Reference Storm are not actual sea state conditions from the Gulf of Mexico, but rather proposed sea states to obtain a variety of downward velocities at the hang-off point for this study. The load cases 2 and 7, are actual 100-year sea states conditions for the Gulf of Mexico in the condition for Winter storm and hurricane following the indicated by tables in the DNVGL-OS-E301 standard.

6.3.4 Soil-riser Interaction

According to Gemilang, 2015; "The soil-riser interactions are modeled by linear soil stiffness and friction. The suitable friction coefficient and soil stiffness are chosen to model the interaction between the riser and the seabed." The parameters are indicated in Table 6.6. These data were used in the thesis "Feasibility Study of Selected Riser Concepts in Deep Water". (Gemilang, 2015)

Table 6. 5: Soil-riser interaction Parameter

Parameter	**Value**
Normal friction parameter	0.5
Axial friction coefficient	0.5
Vertical soil stiffness	10 kN/m^2
Horizontal lateral or axial soil stiffness	100 kN/m^2

6.3.5 Hydrodynamic Coefficients

The hydrodynamic coefficients choose in this project are shown in Table 6.5. The added mass coefficient follows the next expression, (C_A= C_M-1).

Table 6. 6: Hydrodynamic Coefficient

Coefficient	**Value**
Added Mass Coefficient, C_A	1.0
Inertia Coefficient, C_M	2.0
Drag coefficient, C_D	1.1

6.4 Vessel Motions

6.4.1 De-coupled and Couple analysis

The dynamic response of the riser depends mainly on the vessel motion. As mentioned before, there are two types of analysis: Coupled and De-coupled.

Coupled analysis required more extensive computational effort. On the other hand, in the de-coupled analysis; for this, floater motion has not relation with the dynamic behavior of the mooring lines and riser. In this case, they are study separately.

The de-couple analysis contemplates the wave frequency floater motion as dynamic excitation of the wave and the low frequency motion consider as floating unit offset quasistatically. The Wave Frequency floater motions is determined by the Response Amplitude Operator (RAO) data of the floater.

6.4.2 Host Platform

Initially in this project work, a Deep Draft Floater (DDF) was used for the analysis. But, after the screening of the downward velocity in the hang-off point selected, the SCR worked perfectly in the load cases proposed, especially in the load case with 3-hours sea state hurricane condition (Hs=15.8m, Tp= 16.9) coping a maximum downward velocity of 2.3m/s. The results obtained for downward velocity for the different load cases in the DDF is describe in chapter 7.1. The Deep Draft Floater showed to have a better response for harsh sea-state as occurred during a hurricane. It is worth mentioning that DDF faces challenges such as complex study of dynamic behavior, challenges related with increase of mooring line weight, fabrication, transportation and installation.

Thus, for a proper study and screening of the downward velocity at the hang-off point for the different riser configurations and application of residual curvature method, it was decided that a Semi-submersible should be selected.

According to Gemilang, 2017; "Semi-submersibles have good motion response and are used for drilling and production. Semis have natural periods of heave above the typical natural wave period range", thus works out of the area of resonance, this is the main reason the semis are common choice for deep water fields.

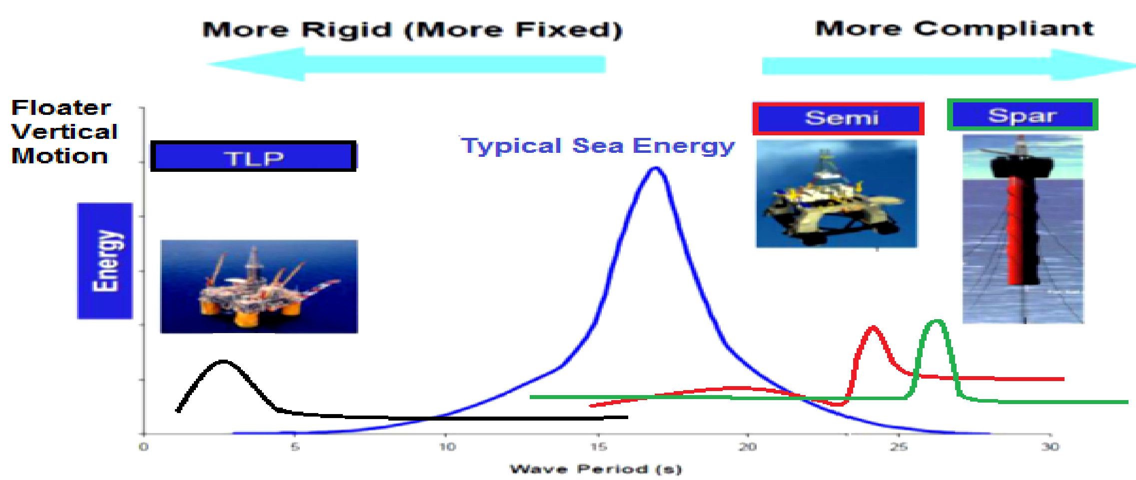


Figure 6. 2: Floater motion Comparison – Heave natural period and wave spectrum

The RAO data of the Deep Draft Floater and Semi-submersible for this thesis is confidential and property of Subsea7, therefore not given in this report.

6.5 Riser Features and Data

6.5.1 Wall Thickness calculation

The DNV-OS-F101 standard is follow as the main guideline for calculating the pipeline's minimum required wall thickness. The material used for construction of the riser is grade X65. (DNV, 2007)

The riser is content oil with density of oil 800 kg/m^3. The design pressure is 920 bar in test condition and 800 bar in operating condition. In this way, this line is considered a high-pressure line, typical on deepwater developments at the GoM. A water depth of 1500 m is considered to calculate the maximum hydrostatic pressure at the bottom in the seabed. Pipeline Engineering Tool (PET) software is considered for the unity check and wall thickness calculation. (Appendix A)

Table 6.7 illustrates the minimum wall thickness results obtaining 39mm for steel pipe with an internal diameter of 10 inches.

Table 6. 7: Minimum wall thickness (Material: X65)

Burst (Operating condition)	Collapse	Propagating Buckling	Burst (Test Condition)
38.6 mm	17,07 mm	24,89 mm	32,41 mm

6.5.2 External Coating

A uniform coating is applied along the entire riser length. The main intention for the use of coating in the risers are mechanical protection, thermal insulation and corrosion protection (Karunakaran, Meling, Kristoffersen, & Lund, 2005)

The following describes the property of external coating:

- ✓ Density: 700 kg/m^3
- ✓ Wall thickness: 2" → 50.8 mm

6.5.3 Upper End Termination

Free hanging risers are usually installed with a flex joint at the top end to relieve stress at the interface of dynamic riser and the semi. As (Gemilang, 2015) mentioned; "For the extreme condition analysis, the pin joint configuration is used to replace the flex joint. Thus in the extreme loading conditions, the top end is modeled as pinned with zero stiffness in bending and twisting". The top end is modeled as pinned due to that the flex-joint stiffness is not affecting in the analysis of the riser for response in extreme loading conditions (Karunakaran et al., 2005). Upper part of Figure 6.3 illustrates the definition pin-jointed node in OrcaFlex. End A is the top end and End B is the anchor point down in the seabed. On the other hand, for fatigue analysis, the flex joint option is used considering a stiffness of 20 kN.m/deg for x, y bending and twisting at the top, node End A. This is shown in the lower part of Figure 6.3.

	Stiffness (kN.m/deg)		
End	x bending	y bending	Twisting
A	0,00	~	0,00
B	Infinity	~	Infinity

	Stiffness (kN.m/deg)		
End	x bending	y bending	Twisting
A	20,00	~	20,00
B	Infinity	~	Infinity

Figure 6. 3: Definition of Pin-jointed node and Flex joint in OrcaFlex
End A is the top end and End B is the anchor point down in the seabed.

6.5.4 Riser Properties

The material selected for the riser is a Grade X65 and the internal diameter is 254mm. With the calculation made using DNV-OS-F101, considering burst, collapse and buckling propagation, the final result for the external Diameter is 332mm. As mentioned in the upper termination selection chapter 6.5.4, the values for stiffness are different for the fatigue analysis (20 kN.m/deg) and extreme condition analysis (0 kN.m/deg). The ovality is 2% and the Well Head Pressure (Pd) is 800 Bar. With this, being a High-Pressure Line.

Table 6. 8: Riser data (With Grade X65 as type of material) (Gemilang, 2015)

Parameter	Symbol	Value	Unit
Outer Diameter	OD	332	mm
Internal Diameter	ID	254	mm
Wall thickness	t	39	mm
Steel Density	ρ_s	7850	Kg/m^3
Content Density	ρ_c	800	Kg/m^3
Ovality	f_0	2	%
Well Head Design Pressure	Pd	800	Bars
System Test Pressure	Pt	920	Bars
Flex joint rotational stiffness (Pin Joint)*	K	20 (0)	kN.m/deg
Modulus Elasticity	E	207	GPa
Poisson Ratio	V	0.3	
Specified Minimum yield Stress	SMYS	448.2	MPa
Specified Minimum Tensile Strength	SMTS	530.9	Mpa

* Flex joint for fatigue analysis and Pin Joint for Extreme analysis

6.5.5 Residual Curvature Section Configuration

Two types of lines will be used, one is called the Steel Catenary Riser, and the second, section with Residual Curvature. Figure 6.4 illustrates how to introduce the residual curvature section in the riser in the software OrcaFlex. To apply this un-straightened section, it is necessary to use the option pre-bent in line edition. For this, torsion must be included in the line data. For more details on how to apply pre-bent option refers to appendix C.

Figure 6. 4: Example of introduction of pre-bent curvature

Line	Section	Pre-bent Curvature (rad/m)		Cumulative Values	
Type	Length (m)	x	y	Length (m)	Segments
Steel Catenary Riser	200,000	0,00000	0,00000	200,000	100
Steel Catenary Riser	1133,24	0,00000	0,00000	1333,24	327
Section with Residual Curvature	50,000	0,00000	0,01000	1383,24	377
Section with Residual Curvature	100,000	0,00000	-0,01000	1483,24	477
Section with Residual Curvature	100,000	0,00000	0,01000	1583,24	577
Section with Residual Curvature	50,000	0,00000	-0,01000	1633,24	627
Steel Catenary Riser	600,000	0,00000	0,00000	2233,24	747
Steel Catenary Riser	600,000	0,00000	0,00000	2833,24	867

In OrcaFlex, the residual curvature section can be seen in red color to differ from the conventional SCR (in yellow). This is shown in Figure 6.5.

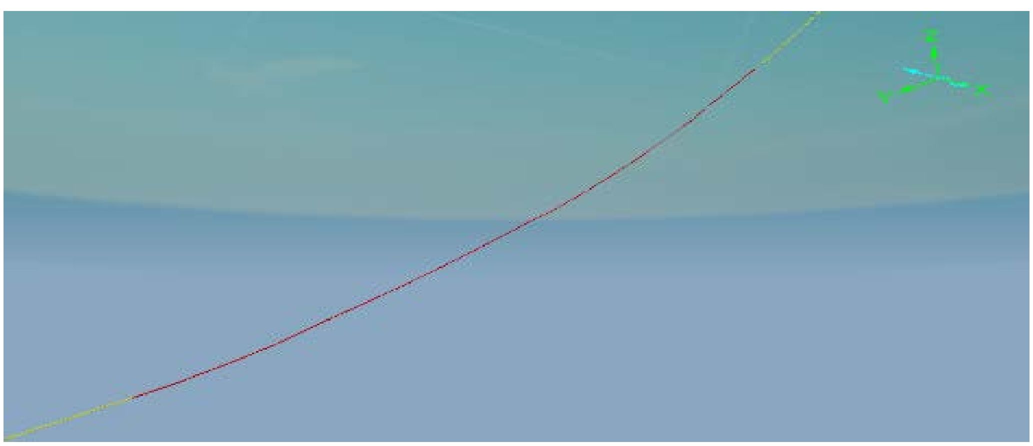


Figure 6. 5: Section of the riser with residual curvature (In red)

6.6 Analysis of Limit States

6.6.1 Design of Load Cases for ULS and ALS

By checking DNV-OS-F201, a proper set of load cases have to be chosen to (DNV , 2010a):

- ✓ Show both permanent and temporary conditions
- ✓ Show the range of operating conditions and functional applications
- ✓ Produce extreme combined for the purpose to analyze load effects
- ✓ Show the different Limit States, ULS, ALS, SLS.
- ✓ Analyze variation of critical parameters at different locations along the whole riser.

The three locations for the application of the load cases are Near, Far and Mean, as illustrated in Figure 6.6.

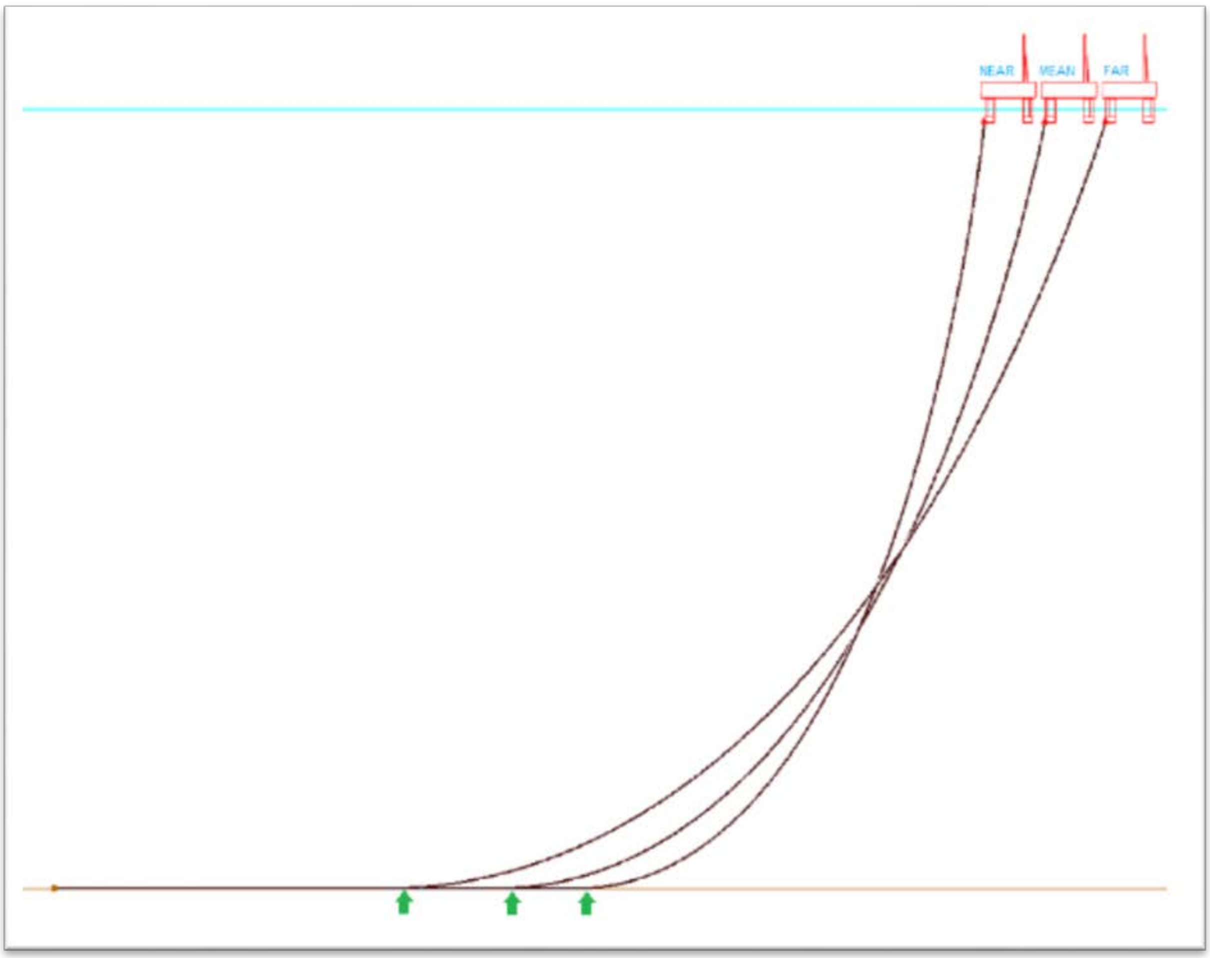


Figure 6. 6: Near, Mean and Far location for the SEMI. (Gemilang, 2015)

The load cases are applied in 180° as well as 0° angle direction for Near and Far position with corresponding semi position as illustrated in Figure in the design cases matrix, ULS will be 5% of the water depth and ALS is taken as 6% of the water depth. This is descried in Table 6.9.

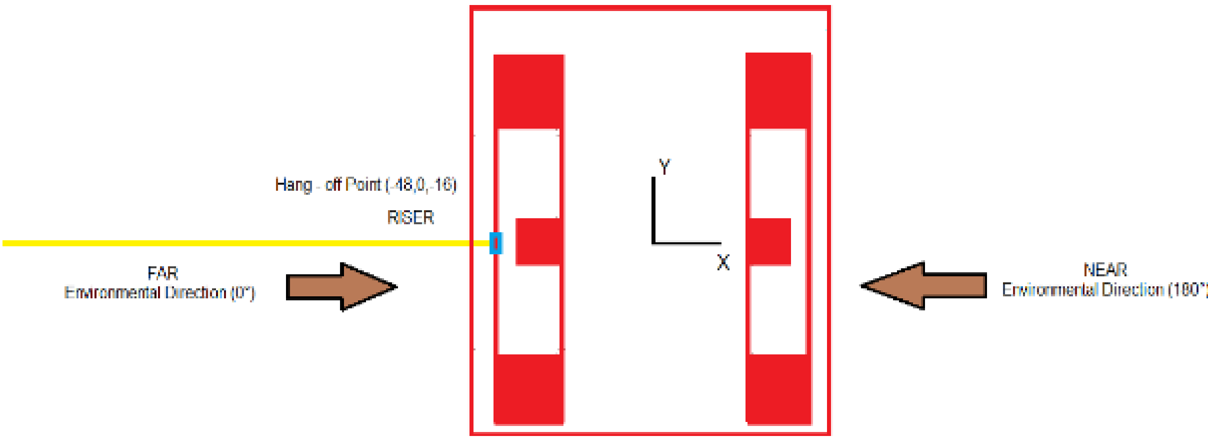


Figure 6. 7: Environmental Direction for the loads.

Table 6. 9: Case and limit state with load type and environmental direction. (Gemilang, 2015)

Case / Limit state	Load type	Environmental load direction	Distance (x)	Offset
Static	Functional	-	0 m	Mean
Dynamic – ALS	Functional + environmental	0°	90 m	Far
Dynamic – ALS	Functional + environmental	180°	-90 m	Near
Dynamic – ULS	Functional + environmental	0°	75 m	Far
Dynamic – ULS	Functional + environmental	180°	-75 m	Near

Table 6.9 mentions the cases and limit states studied in this thesis. Considering the load type and environmental direction. Starting with Static case which uses mean offset and not environmental loads. The second and third case use Ultimate Limit State considering environmental load direction in 0° for far and 180° for near, with 75m of distance in X-directions for the offset. Likewise, for the cases 4 and 5 use Accidental Limit State with 90m of distance for the offset.

6.6.2 Calculation of LRFD Utilization

For code check, the standard DNV-OS-F201 will be used as mentioned in chapter 3. The Figures 6.8 and 6.9 show the values used for the factors and properties for the riser configuration in OrcaFlex. For ULS and ALS the load factors are different according to what was stated in chapter 3.

Figure 6. 8: Load Factors and line type factors in ULS. DNV-OS-F201. As used in OrcaFlex

Functional, γF	Environmental, γE	Condition, γc	Moment Condition, γcm	Reduced Functional, γRF	Reduced Environmental, γRE
1,10000	1,30000	1,00000	1,00000	0,91000	0,77000

Safety Class Factor, γSC	Material Resistance Factor, γm	Fabrication Factor, αfab	WSD Usage Factor, η
1,2600	1,1500	1,0000	0,7500

Figure 6. 9: Riser properties. DNV-OS-F201. As used in OrcaFlex.

fy (kPa)	fu (kPa)	Young's Modulus, E (kPa)	Out Of Roundness, f0
448,20E3	530,90E3	207,00E6	0,0200

Chapter 7. Study for Extreme Conditions

7.1 Introduction

The study for the extreme response analysis is made in this chapter considering the SCR, WDSCR and proposed a configuration for the SCR with residual curvature method, which can be called **RCSCR.** The first two are modelled and simulated in order to have a point of comparison and validation against the "Steel Catenary Riser with implemented Residual Curvature Method" RCSCR.

The following describe the disposition of the risers:

- ✓ The riser is attached to the Semi at 16 meters below the mean sea water level.
- ✓ The distance between the anchor point at the seabed and the center at mean location of the semi is 2000m.
- ✓ The total length of the riser is 2796 m is static mean position for SCR. It will change slightly when applying sections with residual curvature. If the same top hang-off angle is used,
- ✓ The hang off angle at mean position is 15° in relation to the vertical plane.
- ✓ For ULS, offset is 5% of the water depth. 75m
- ✓ For ALS, offset is 6% of the water depth. 90m
- ✓ With fluid content (800kg/m^3) and coating (2" wall thickness)
- ✓ The riser is pressurized with 800 bars at subsea level (well head).
- ✓ Position of the hang-off point: X= -48m, Z= -16m (x=0, y=48, z=-16 Semi coordinate system)
- ✓ Semi, Heading = 90°; respect to global coordinate system.

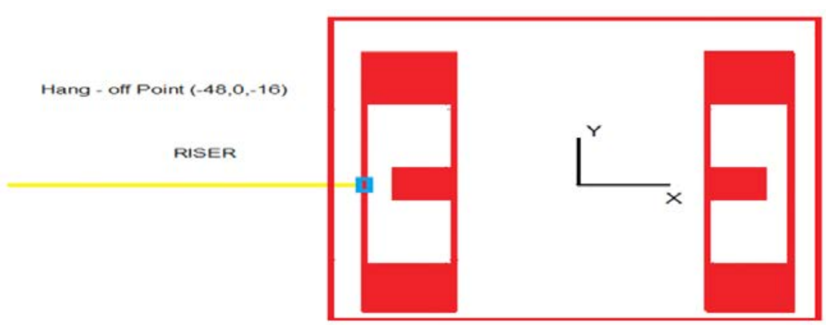


Figure 7. 1: Plane view of SEMI coordinate system and hang-off point location.

The general procedure chose for this study follows the one used by Gemilang, 2015; It is summed up as follows:

- ✓ For each load case seed components are selected
- ✓ Static analysis is performed which is used to determine an optimum static configuration for the conventional as well as the Weight Distributed Steel Catenary Riser, and the SCR with some percentage of water depth of its arc-length with a section of residual curvature, named as RCSCR.
- ✓ Dynamic analysis which allows a strength analysis in the extreme sea states with influence of both the current and wave for each load case.
- ✓ Conclusion for this section.

The same methodology used in the theses "Feasibility Study of Selected Riser Concepts in Deep Water and Harsh condition" (Gemilang, 2015) and "Study of Residual Curvature Applied to the Problem of Dynamic Compression in Rigid Risers in Free Catenary" (Ramiro, 2018) will be used in this thesis to study SCR Design issues and merits with the application of Residual Curvature Method.

7.1.1 Selection of seed Components

For the load cases, according to Gemilang, 2015; "20 simulations of 3-hours duration are performed with different randomly seed components to generate different sea-states realizations for each load case." Therefore, 7 x 20 simulations are executed. Following the reference mentioned, "the 20 random seed components are ordered from 1 to 20 and the order of the seed is name as "m". The different sea-state realizations generate different velocities at the hang-off point." Obtaining 20 maximum responses for the downward velocity at the hang-off point. Then, these seeds are arranged from the smallest to the largest and in that way, they can be sorted and fit in an extreme value distribution. The 90% percentile is obtained from this arrangement.

Table 7.1 summarized the result of the selection of seed component "m" for all the load cases. As stated by Gemilang, 2015; "the downward velocity at the hang-off point in the table correspond to the 90% percentile response given the extreme value distribution."

For the fitting, Gumbel Distribution $F_X(x)$ will be used. This distribution is implemented to model the maximum or the minimum number of samples of various distributions. The density function of the underlying variable decays exponentially and the number of observations "x" for wave heights have to be sufficiently large to obtain a reasonable accuracy. The following equations describe the Gumbel Distribution:

$$F_X(x) = exp\left\{-exp\left\{-\frac{x-\lambda}{\kappa}\right\}\right\} \qquad \text{Eq. 7.1}$$

$$Expected\ value: \qquad E[X] = \lambda + 0.57722\kappa$$

$$Standard\ Deviation: \qquad STD[X] = 1.28255\kappa$$

Where

$x = \lambda + \kappa[-\ln(-\ln F_X(x))]$; Observation for a given Probability F(x)

Originally in this project work, a Deep Draft Floater (DDF) was used for the analysis. However, after the screening of the downward velocity in the hang-off point selected, the SCR performed correctly in the load cases proposed as shown in Table 7.1, especially in the load case 7 with 3-hours sea state in hurricane condition for Gulf of Mexico (Hs=15.8m, Tp= 16.9) handling the maximum downward velocity of 2.31 m/s. (Table 7.1 is adapted from Gemilang, 2015. 3-h storm with corresponding seed component. Considering 10-year current profile for GoM. This table is not used for the final analysis.)

Table 7. 1. Load cases applied to the DDF (Not used for the analysis of RCM on SCR)

Sea State	**Wave Characteristics**	**Hs (m)**	**Tp (s)**	**γ**	**Downward Velocity at the hang-off (m/s)**	**Seed order (m)**	**Wave Seed for m**
Reference Storm	*Load Case 1*	*4*	*16*	*1*	*0.53*	*3*	*755*
Reference Storm	*Load Case 2*	*5*	*16*	*1*	*0.66*	*3*	*755*
Reference Storm	*Load Case 3*	*6*	*16*	*1*	*0.79*	*3*	*755*
*Winter Storm**	*Load Case 4*	*7.3*	*12.8*	*1.352*	*0.78*	*7*	*1789*
Reference Storm	*Load Case 5*	*10*	*16*	*1*	*1.32*	*3*	*755*
Reference Storm	*Load Case 6*	*14*	*16*	*2.299*	*1.83*	*4*	*638*
*Hurricane**	*Load Case 7*	*15.8*	*16,9*	*2.365*	*2.31*	*10*	*5133*

* Typical 100-year Hs and Tp for GoM under Winter Storm or Hurricane Conditions, DNVGL-OS-E301

Tables 7.1 and 7.2 show the differences in response for heave motion for two types of offshore platforms, a Deep Draft Floater and a Semi-Submersible. It can be seen how the DFF have a lower response in the amplitude of the heave velocity motions, giving a maximum downward velocity for hurricane condition of 2.31 m/s while the Semi reaches a downward velocity of 4.27 m/s. DDF is a proper option when the floating platform selection is made for GoM conditions and the used of SCR is necessary.

Then, as indicated in chapter 6.4.2, the platform selected is a Semi-submersible, with this, a better study of different riser configurations and application of residual curvature method can be performed. Table 7.2 presented the response of downward velocity at the hang-off point for the selected Semi-Submersible.

Table 7. 2: Load cases, 3-h storm with corresponding seed component for SEMI

Sea State condition	**Wave Characteristics**	**Hs (m)**	**Tp (s)**	**γ**	**Downward Velocity at the hang-off (m/s)**	**Seed order "m"**	**Wave Seed for "m"**
Reference Storm	Load Case 1	4	16	1	1.18	5	1159
Winter Storm*	Load Case 2	7.3	12.8	1.352	1.81	5	1159
Reference Storm	Load Case 3	8	16	1	2.35	5	1159
Reference Storm	Load Case 4	9	16	1	2.64	5	1159
Reference Storm	Load Case 5	10	16	1	2.94	5	1159
Reference Storm	Load Case 6	11	16	1.224	3.31	4	829
Hurricane*	Load Case 7	15.8	16.9	2.365	4.27	8	3098

* Typical 100-year Hs and Tp for GoM under Winter Storm or Hurricane Conditions, DNVGL-OS-E301

The Sea State conditions 1, 3, 4, 5 and 6 mentioned in Table 7.2 as Reference Storm are not actual sea state conditions from the Gulf of Mexico, but rather proposed sea states to obtain a variety of downward velocities obtained at the hang-off point for this analysis, making possible to execute a screening of the different downward velocities for the study for the different riser configurations, and study more deeply the capacity of the riser with un-straightened section applied.

7.2 Analysis for conventional SCR

The study of the Steel Catenary Riser is taken into account to have a better understanding of the static and dynamic behavior of the rigid riser with the purpose of making validation and comparisons with the riser configuration with the applied residual curvature.

7.2.1 Static Analysis of SCR

The optimum static configuration and static analyses for the conventional Steel Catenary Riser with coating for validation is made in this chapter. Non-coating riser option is not taken into account in this study.

The conventional SCR hang from the semi-Submersible as illustrated in the Figure 7.2. This static equilibrium gives static configuration. As mentioned before, the anchor point is at 2000m distance from the zero coordinates of the Semi, the top angle relative to the vertical is 15º. Using calculation tool of OrcaFlex, the total riser length is 2796m for static mean position.

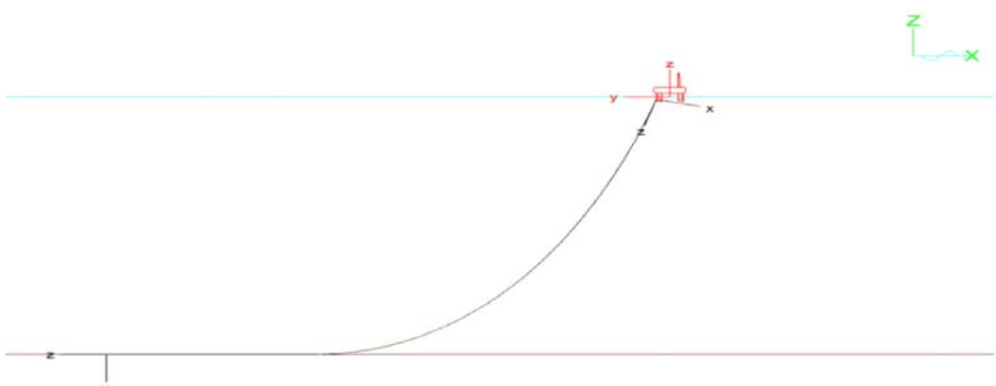


Figure 7. 2: Global coordinate system and coordinates for SEMI and SCR.

The analysis starts with a comparison between the SCR empty and full, with content fluid inside and pressure of 800 bar applied at seabed level, in mean position as shown in the Table 7.3.

Table 7. 3: SCR static results – Full and Empty – Functional loads only

SCR Static ULS	**Full**	**Empty**
	Mean	**Mean**
Hang off Angle (°)	15°	14,7°
Effective top Tension (kN)	4434	3610
Max. Bending Moment (kN.m)	128	125
Max. DNV LRFD Utilization	0,35	0,07

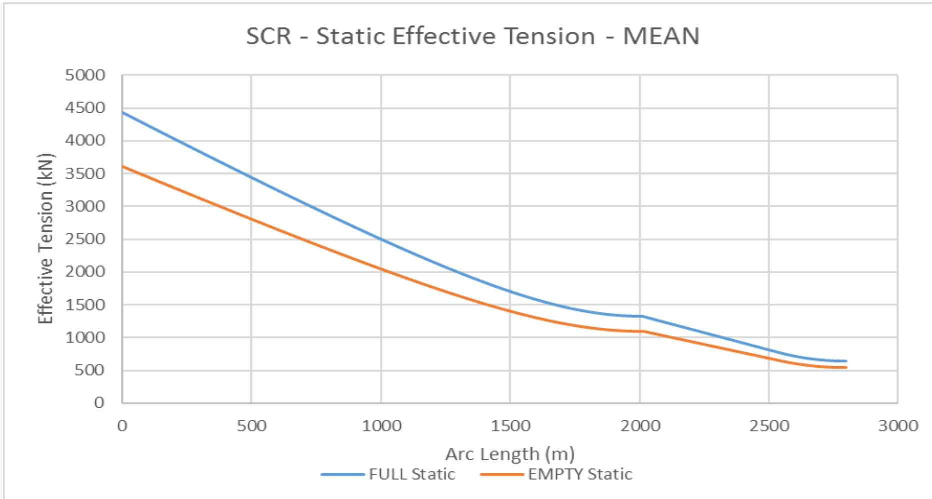


Figure 7. 3: SCR – Full & Empty - Static Effective Tension

It can be seen in Figure 7.3 that the static effective tension is relate to the riser arc-length. Here, the maximum effective tension is happening up at the hang-off point and the lowest value at the anchor point, in the middle after the TDP become almost flat, as expected is larger for the riser with content.

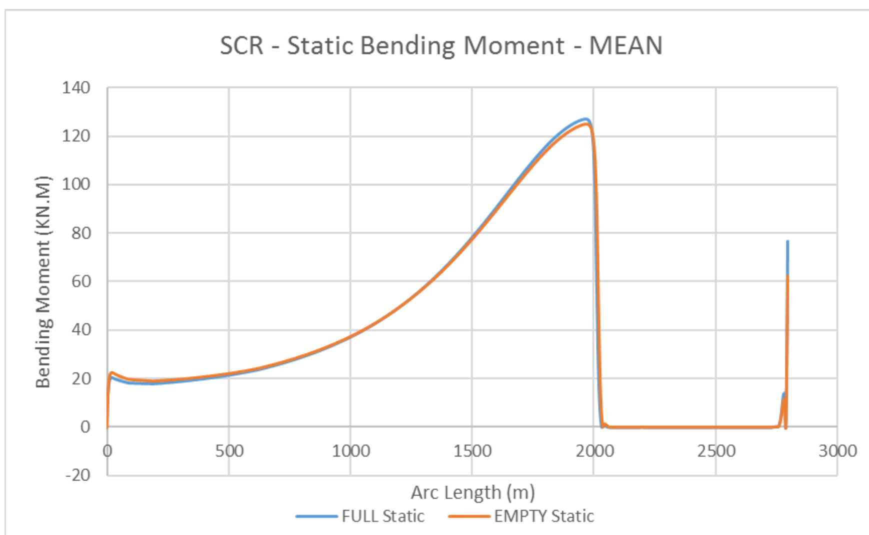


Figure 7. 4: SCR - Static Bending moment – Mean position

From Figure 7.4, the bending moment along the risers length behaves the same with its maximum at the Touch down Zone TDZ.

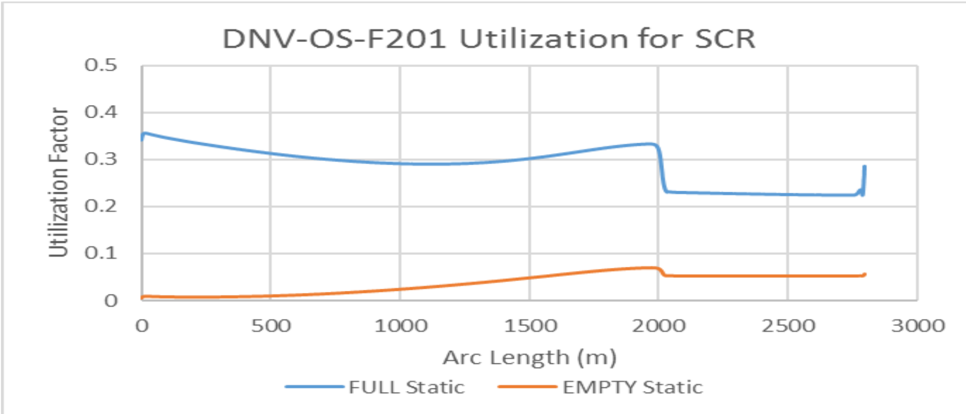


Figure 7. 5: Static Utilization of SCR Mean, Full and Empty

From Figure 7.5, it can be seen that the riser with content has more utilization value along the riser with its maximum at the hang-off point, a second maximum in the TDZ. The SCR empty has a maximum utilization factor of 0.07 while the maximum utilization factor for the SCR with content is 0.35.

It can be concluded that the bending moment IS more important than the effective tension as have more impact in the Utilization Factor and will be the driving design parameter for the riser. Likewise, the SCR with content (full and pressurized) has to be consider from now on for the analysis as has more influence on the Utilization Factor.

The different riser configurations are study only with coating. The analysis continues comparing the riser full (Pressure and Fluid content inside) considering position Near, Mean and Far ultimate limit state ULS (offset=75m). Only coating option for the different riser configurations will be analyze.

For the SCR in static analysis and mean position the touch down point TDP has the following locations (in the global coordinates):

- With Coating: x=-1218m, z=-1500m, Arc length= 2015m

Table 7. 4: SCR Static Result – ULS

SCR Static full ULS	Near	Mean	Far
Hang off Angle (°)	11,4°	15°	19°
Effective top Tension (kN)	4111	4434	4860
Max. Bending Moment (kN.m)	168	128	97
Max. DNV LRFD Utilization	0,36	0,35	0,38

According to the Table 7.4, the top angle relative to the vertical varies and is higher for the Far position. It can be seen the different offset positions give significant impact on the configuration, especially for the bending moment. The TDP and hang-off changes for each location.

Figure 7. 6: SCR - Static Effective tension – Coating and full

From Figure 7.6, the effective tension is larger along the riser for the Far position and lower for the riser in Near position. The maximum effective tension occurred at the hang-off point.

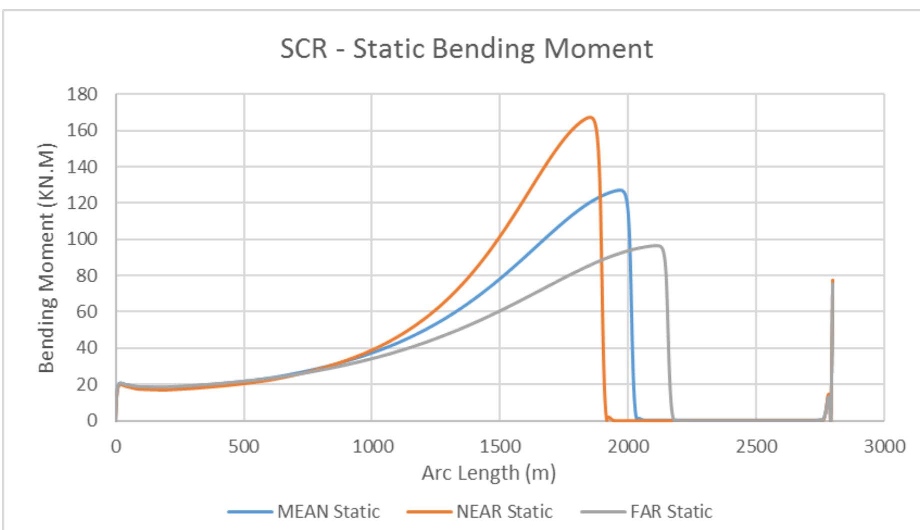


Figure 7. 7: SCR - Static Bending Moment

In Figure 7.7, the maximum bending moment for the 3 locations occurred at the TDZ. The bending moment is smaller near the hang-off point. The highest bending moment occurred when the riser is in near position.

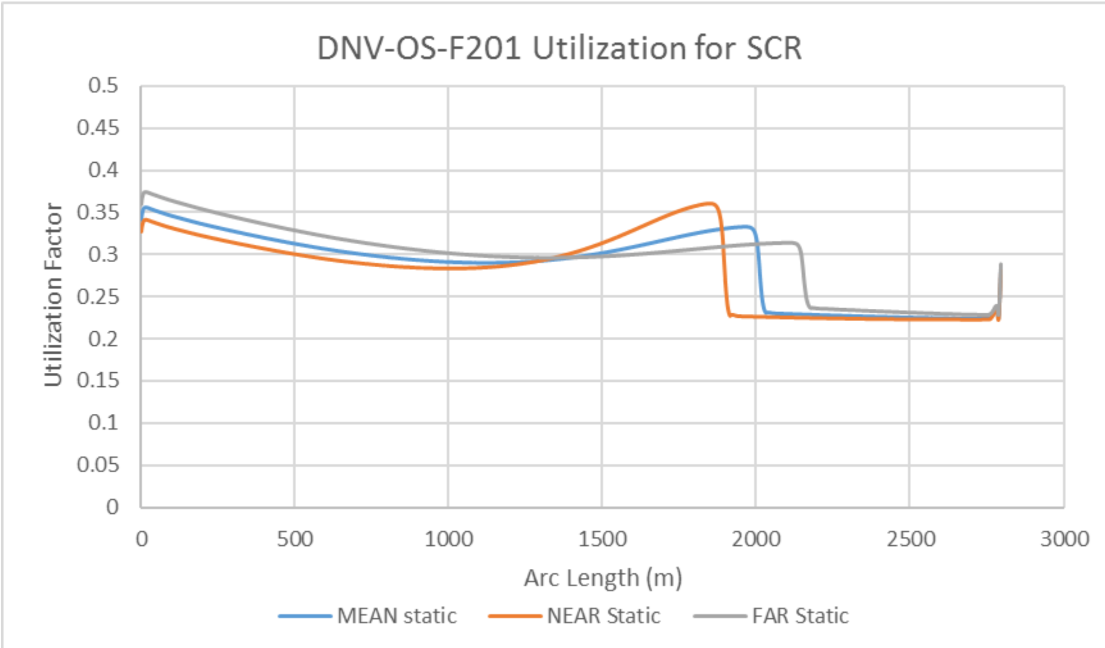


Figure 7. 8: SCR Static Utilization for three locations.

From Figure 7.8, the near offset position obtained the maximum utilization at the TDZ. However, the riser in Far offset position has the highest utilization factor for this case at the hang-off point. This indicates that for the touchdown zone the bending moment influence the most, but for the hang-off point, the utilization is influenced by both the top effective tension and the bending moment.

7.2.2 Dynamic Analysis for SCR

The SCR has 39mm wall thickness and is not only full of internal fluid with 800kg/m^3 of density but also pressurized at 800 bars down in the subsea wellhead to approach the analysis to a real scenario in the industry. Table 7.5 shows the summary of the response to strength for the SCR for both ULS and ALS limit states in two location Near and Far, and for the load case (LC) 4 which has a 90-percentile for 2.64m/s of maximum downward velocity at the hang-off point. The configuration in ALS-Far shows the largest effective tension. There is compression for ULS-Near and ALS-Near configuration. The maximum bending moment occurred in ULS-Near location. Similarly, the maximum utilization occurred for ULS-Near. Even though there is compression in this load case with downward velocity of 2.64m/s, the utilization is still under 1. The most critical case is for ULS-Near configuration.

Table 7. 5: SCR Strength Response Summary LC=4, Max. DV=2.64m/s

Load case 3 Full	**Intact ULS**		**Damage ALS**	
	Near	**Far**	**Near**	**Far**
Max. Effective top Tension (kN)	5353	6756	5240	6939
Max. Compression (kN)	170	0	121	0
Max. Bending Moment (kN.m)	834	258	795	230
Max. DNV LRFD Utilization	0.98	0.54	0.80	0.48

For load case 3, with ULS-Near configuration the minimum effective tension is non-negative, there is no compressive forces throughout the conventional SCR for downward velocity of 2.35 m/s as shown in Figure 7.9. If only the utilization factor is considered as acceptable criteria, the maximum downward velocity at hang-off point that SCR can withstand is 2.64m/s.

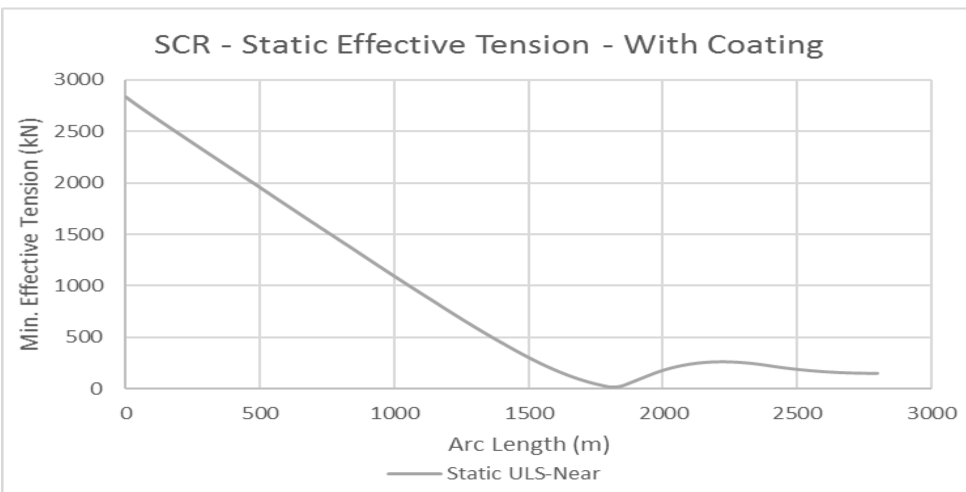


Figure 7. 9: SCR Dynamic Analysis – ULS in LC=3, Max. DV=2.35m/s

For load case 5, where the downward velocity is 2.94m/s, the maximum utilization factor goes beyond one for the ULS in Near position as seen in Table 7.6. With this, it is possible confirm that the SCR can work until 2.64m/s properly. This indicates that the maximum downward velocity at the hang-off point induces the maximum utilization at the TDP for the SCR. These results are similar that the ones obtained by Gemilang, 2015.

Table 7. 6: SCR Strength Response Summary LC=5, DV=2.94m/s

Load case 5 Full	**Intact ULS**		**Damage ALS**	
	Near	**Far**	**Near**	**Far**
Max. Effective top Tension (kN)	5531	7075	5406	7276
Max. Compression (kN)	369	0	298	0
Max. Bending Moment (kN.m)	1077	349	1011	310
Max. DNV LRFD Utilization	1,21	0,57	0,96	0,50

For the different configurations and limit states, the ULS-Near with load case 5 with downward velocity of 2.94m/s, a utilization of 1,21 is obtained, which is no longer within the allowable design criteria. Figure 7.10 illustrates ULS and ULS limit states for Near and Far location in relation with the Utilization factor.

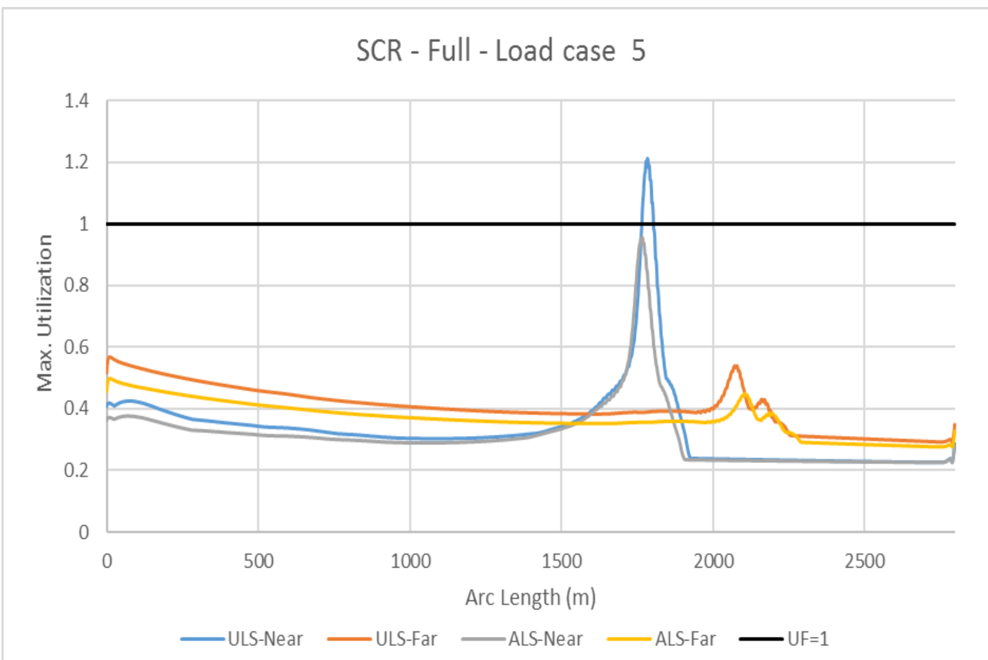


Figure 7. 10: SCR Max Utilization for ULS & ALS, Near & Far

The maximum downward velocities at the hang-off point gives as a result the maximum utilization at the touchdown area for the Steel Catenary Riser. This same result was also obtained by Gemilang in 2015 in its thesis of "study for feasibility of different riser configurations" (Gemilang, 2015). The influence of the downward velocity on the maximum Utilization can be seen in Figures 7.11 and 7.12 where the vertical velocity at the hang-off point and the SCR responses such as effective tension and bending moment at the touchdown point are drawn over time history for ULS-Near configuration.

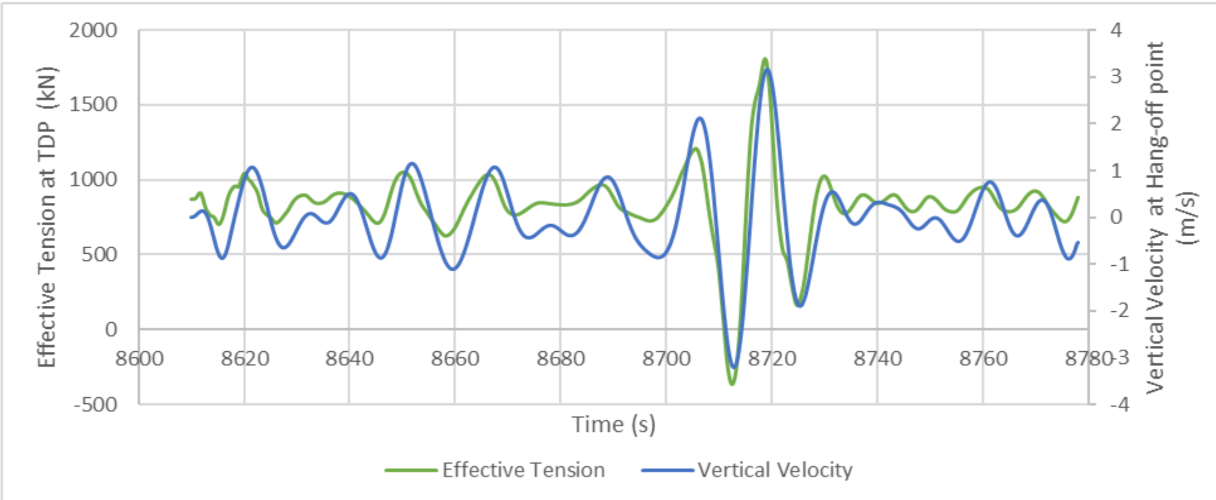


Figure 7. 11: SCR ULS-Near, Time history: Effective tension LC=5

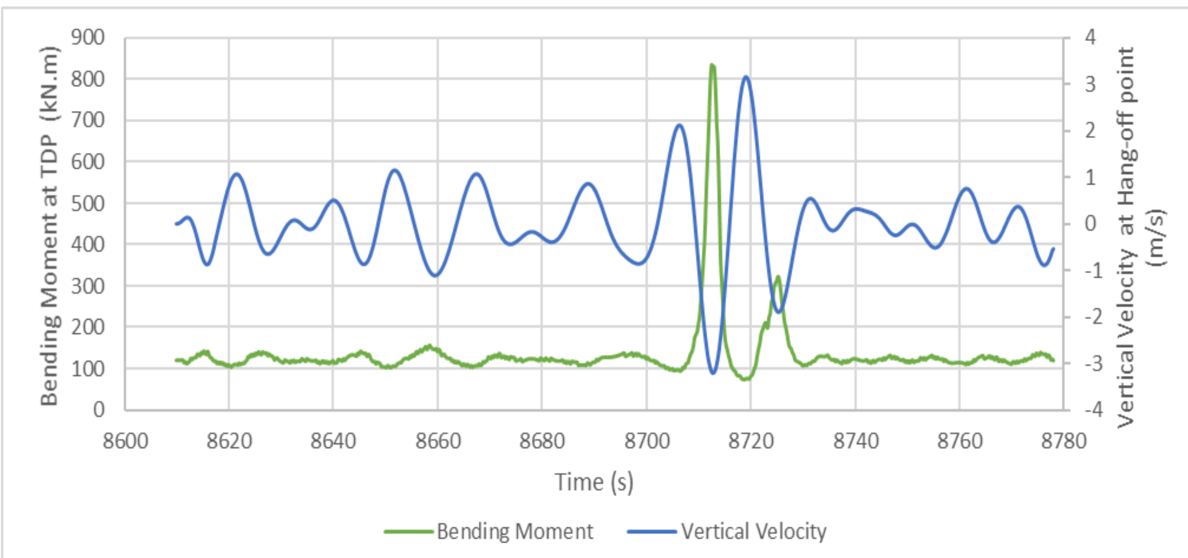


Figure 7. 12: SCR ULS-Near, Time history: Bending moment, LC=5

After this analysis can be concluded that:

SCR ≤ DV at hang-off point of 2.64 m/s ---- Utilization < 1

From Figure 7.13 it can be extracted the extension of the touch down zone for the SCR in ULS-Near configuration for load case 5. This will be helpful in order to avoid touching the touch down zone when applying the residual curvature section.

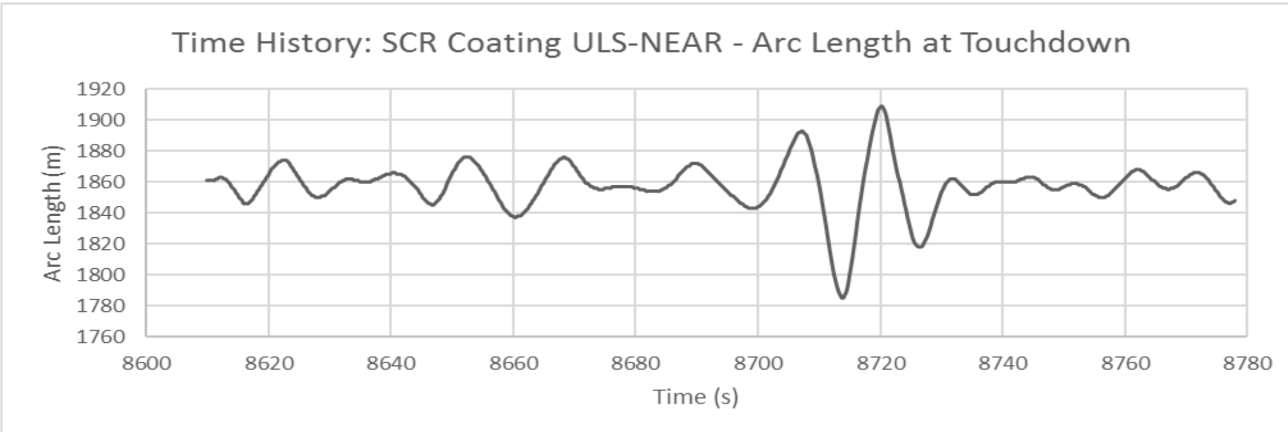


Figure 7. 13: SCR ULS-Near, time history: Arc Length Touchdown

- Max. Arc Length (m)=1909.2
- Min. Arc Length (m)=1785.2
- TDZ (m) = 124m ; For load case 5

For the study of application of residual curvature on the SCR and comparison, this study report will be focused on the riser in ULS-Near configuration and with full content, as has been shown to be the most critical case. These results are similar as the one found in the thesis of “Feasibility study of selected riser concept in deep water and harsh environment”. (Gemilang, 2015)

7.3 Analysis for WDSCR

7.3.1 Static analysis for WDSCR

Weight Distributed SCR is analyzed in order to have sufficient data to compare with the SCR with residual curvature (RCSCR) results. The Weight-Distributed Steel Catenary Riser (WDSCR) is a modification of the traditional Steel Catenary Riser. This modification is attained by adding heavy sections at the bottom of the straight part of the traditional Steel Catenary Riser, thus reducing the dynamics of the lower part of the riser and decreasing the dynamic stresses in the area near the touch down point. For this case, in the software OrcaFlex, a heavier coating was used to implement the weight distributed section. The following configuration will be used for the WDSCR:

- Ballast module: 500kg/m
- Install: 36
- Total length of the Weight Distributed section: 360m
- Height from Seabed: 180m
- SCR with Coating

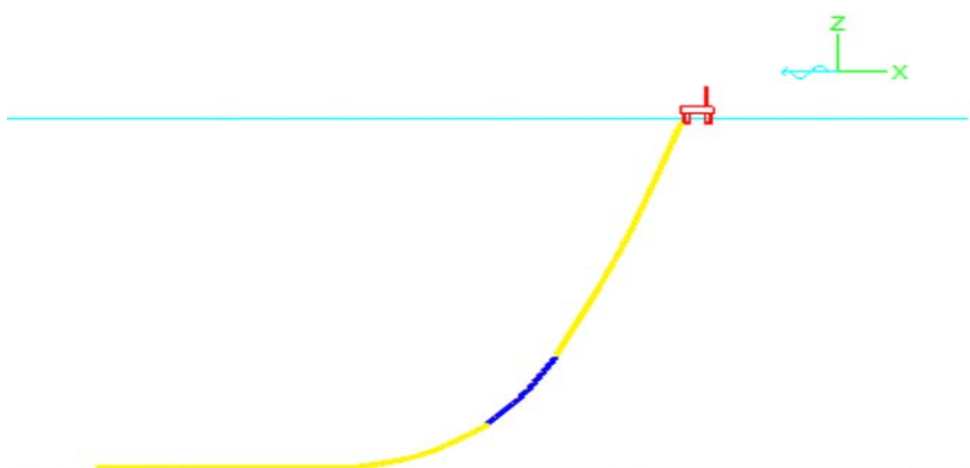


Figure 7. 14. SCR with Weight Distributed Section WDSCR

Table 7. 7: WDSCR Static Result – ULS

WDSCR Static Full ULS	Near	Mean	Far
Hang off Angle (°)	16,6	19,7	23,2
Effective top Tension (kN)	5584	5966	6460
Max. Bending Moment (kN.m)	199	159	128
Max. DNV LRFD Utilization	0,46	0,49	0,53

According to Table 7.7, the top angle relative to the vertical varies and is higher for the Far position as expected. It can be seen the different offset positions give significant impact on the configuration. Comparing WDSCR with Table 7.3 for the SCR, the values of effective tension, bending moment and Utilization are higher for WDSCR for all the configurations.

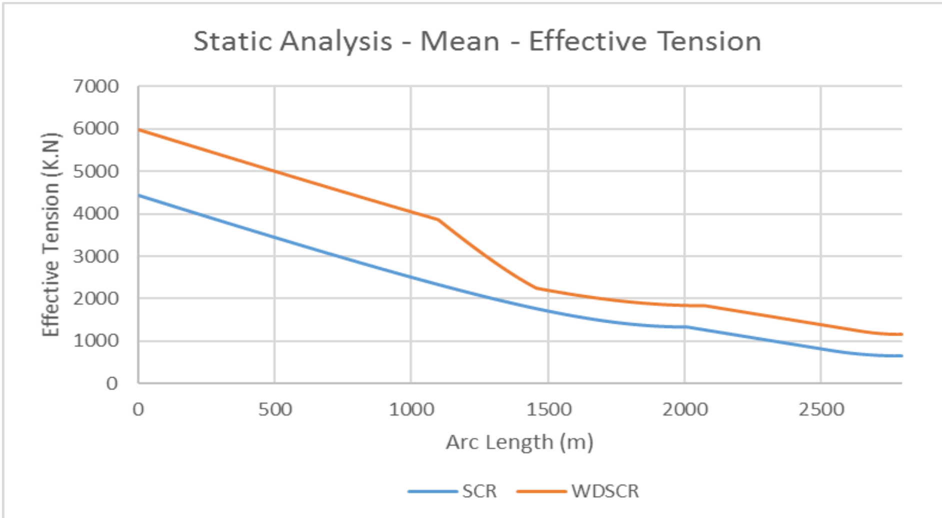


Figure 7. 15: SCR and WDSCR - Static Effective tension

From Figure 7.15, it can be observed that along the riser the effective tension is lower for the SCR.

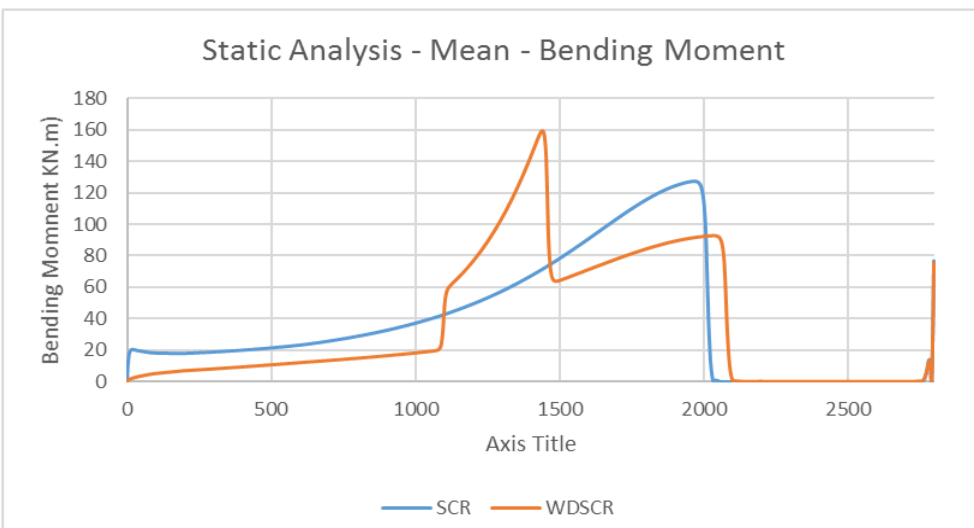


Figure 7. 16: SCR and WDSCR - Static Bending moment

From Figure 7.16, WDSCR has a pick of bending moment in the lower part of the heavy section and it is higher than the bending moment of the conventional Steel Catenary Riser.

7.3.2 Dynamic Analysis WDSCR

Table 7.8 shows the summary of the response to strength for the WDSCR for both ULS and ALS limit states in two location Near and Far, and for the load case (LC) 5 which has a 90-percentile for 2.94m/s of maximum downward velocity in the platform at the hang-off point of the riser. Analysis without coating is not taken into account. There is not compression for most of the configurations except for ULS-Near. The maximum bending moment occurred for the WDSCR in ULS-Near location. Likewise, the maximum utilization occurred for ULS-Near. Even though there is compression in this load case with downward velocity of 2.94m/s, the utilization is still under 1. The most critical case is for ULS-Near configuration as occurred with the SCR.

Table 7. 8: WDSCR Strength Response Summary LC=5, DV=2.94m/s

Load case 5 Full WDSCR	Intact ULS		Damage ALS	
	Near	Far	Near	Far
Max. Effective top Tension (kN)	7545	9074	7385	9302
Max. Compression (kN)	26	0	0	0
Max. Bending Moment (kN.m)	603	188	561	165
Max. DNV LRFD Utilization	0,77	0,72	0,63	0,62

For load case 6, where the downward velocity is 3.31m/s, the maximum utilization factor is higher than the allowable criteria for the ULS in Near position as shown in table 7.9. With this, it is possible say that WDSCR can work at downward velocity up in a value between 2.94m and 3.31m/s. With the load cases used in this study work, it is no possible to determine the exact value. Following the thesis made by Gemilang, the value for the downward velocity obtained was 3.2m/s. (Gemilang, 2015)

Table 7. 9: WDSCR Strength Response Summary LC=6, DV=3.31m/s

Load case 6 Full WDSCR	Intact ULS		Damage ALS	
	Near	Far	Near	Far
Max. Effective top Tension (kN)	7732	9013	7615	9483
Max. Compression (kN)	498	0	427	0
Max. Bending Moment (kN.m)	1018	306	970	312
Max. DNV LRFD Utilization	1,17	0,72	0,93	0,63

After this analysis and checking reference thesis (Gemilang, 2015), It can be said that:

Selected WDSCR ≤ DV at hang-off point of 3.2m/s → Utilization <1

7.4 Parametric Study of RCSCR Configuration

In this chapter study the parameters that will define the geometry and location of the sections with residual curvature. The tornado chart as seen in Figure 7.17 are bar charts used by decision makers to see the parameters and values involve in a sensitivity analysis or parametric study for decision making. In this case, for the best application of the section with residual curvature for the RCSCR. This procedure follow a similar path taken by (Ramiro, 2018)

The procedure applied in this parametric study is as follow:

- Step 1: Selection of Load case.
  Select Load Case for the study: Extreme condition to start, Load Case 7 which describe a 3-h storm in hurricane condition for the Gulf of Mexico.

- Step 2: Determine downward velocity.
  Obtained the maximum downward velocity for the Load Case: For LC 7, the maximum downward velocity is 4.27m/s.

- Step 3: Define parameters and range.
  Define parameter for the base geometry and location of residual curvature section. The parameter to be modify are length, radius of curvature, distance from seabed without using sections of the riser that have contact with seabed, number of sections in row and number of sections applied.

- Step 4: Apply changes for each parameter.
  Apply each parameter running a sensitivity study, selecting the best result for Utilization Factor DNV for the load case.

- Step 6: Fine tuning.
  If Utilization Factor is not under the allowable value (UF<1), then select other load case with a lower downward velocity. Run again steps 1 to 5, until the UF<1.

- Step 7: Select RCSCR configuration.
  Determine the downward velocity for the Load Case selected that gives UF<1. Obtaining best configuration for the RCSCR.

Table 7.10 shows parameters that will be use for the parametric study, this parameter are section length, radius of curvature for the section, distance from seabed (for the application of the un-straightened section without using part of the of the riser that have contact with seabed), number of sections in row and number of sections applied. Likewise, Table 7.10. shows how the step 3 in the procedure apply in this parametric study

Table 7. 10: Parameter for sensitivity study

Parameter	High	Low	Base
Length (m)	750	30	250
Radius of Curvature (m)	400	25	225
Distance from Seabed "No using TDZ" (m)	1200	0	180
Number of sections in row	4	1	1
Number Applied in different locations	2	1	1

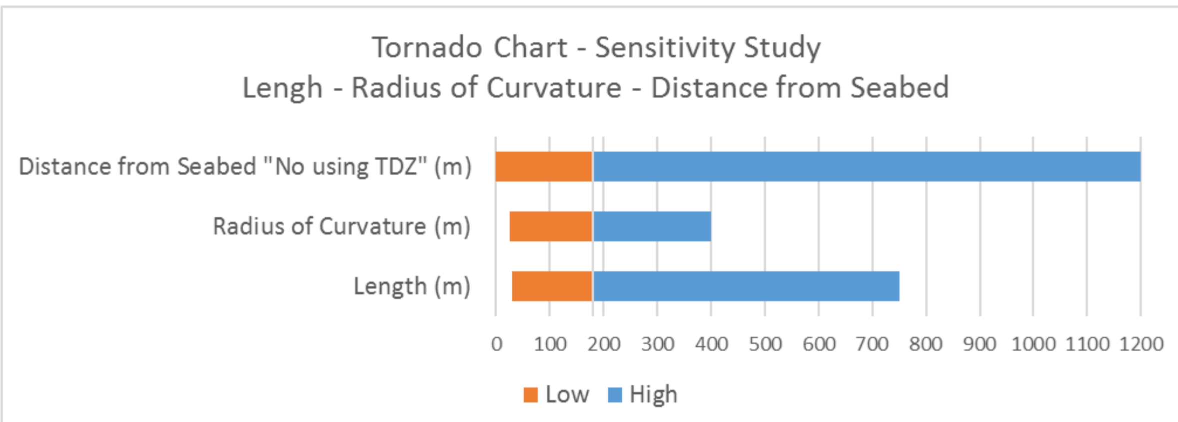


Figure 7. 17. Parameter range for sensitivity study in a tornado chart.

The base geometry for this study is illustrate as show in Figure 7.18, it consists of four subsections with same curvature, the first and fourth are half of the length of the second and third. This base geometry was selected following the study made by (Ramiro, 2018).

Figure 7. 18: Un-straightened section geometry for study, with 4 subsections. (Ramiro, 2018)

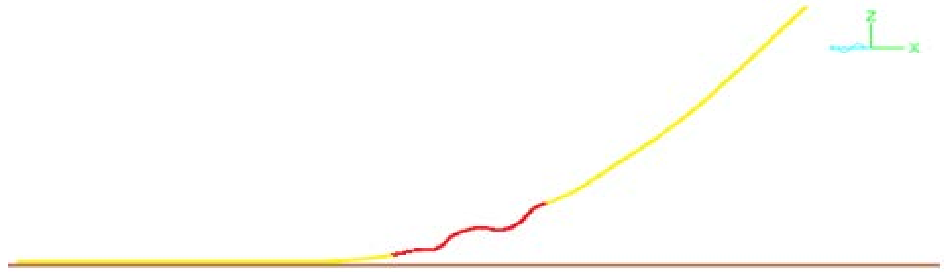


Figure 7. 19: Depiction of the application of residual curvature section (No real values)

The idea is to solve for extreme conditions, and as mentioned, the parametric study and sensitivity will be done initially for load case 7, which is a typical 3-h sea state for a hurricane condition according to (DNV GL, 2015). For this LC, the downward velocity at riser's the hang-off point is 4,27 m/s. Likewise, the configuration for this design will be the ULS-Near load case with coating and full (fluid and pressurized), as in the analysis for SCR shown to be the most critical.

As base case for the section with curvature, the following configuration will be used:

- Radius of curvature: 250m -> 0.004 m^{-1} of curvature
- Distance from seabed of the lower part of the section: 250
- Number of "Cycles" or sections in row: 1
- Number Apply: 1

Clarifying that for the sensitivity analysis, the changes in the un-straightened section affect slightly the arc-length of the riser and thus the top angle at hang-off in relation to the vertical axis. These variations of the top angle at the hang-off will not be taking into account for the sensitivity analysis, but once the final section of the RCSCR is stablished and analyzed together with the comparison that is going to be made, this angle will be taken into account. Its value as mentioned before will be 15°.

For load case 7, with a downward velocity of 4.27 m/s, it is necessary to find the segments of the arc length that are part of the touchdown point. Then avoiding using this area for the implementation of the section with residual curvature. The following data is found for the load case 7 in relation with the touchdown point in the arc length;

- Max. Arc Length: 1939.2 m
- Min. Arc Length: 1756.2 m
- Touchdown Zone TDZ: 183 m

Maximum location for application of Residual Curvature – **Arc Length = 1756 m**

7.4.1 Sensitivity for section length

Using Load case 7 with maximum downward velocity of 4.27m/s at the hang-off point, the sensitivity analysis starts as mentioned for step 3 of the procedure to perform the parametric study. Different lengths will be used for the section with residual curvature, these lengths are related to the percentage they represent compared to the water depth. For example: 30m, 75m, 120m, 180m, 225m, 300m, 750m -> 2%, 5%, 8%, 12%, 15%, 20%, 50% of Water Depth.

For each section, the four subsections will have the following length:

- Length 30: 5, 10, 10, 5 m
- Length 75: 12.5; 25; 25; 12.5 m
- Length 120: 20, 40, 40, 20 m
- Length 180 : 30, 60, 60, 30 m
- Length 225: 37.5, 75, 75, 37.5 m
- Length 300: 50, 100, 100, 50 m
- Length 750: 125, 250, 250, 125 m

Table 7. 11: Sensitivity for change in section length, LC7, DV=4,27m/s

Length of Section with curvature (m)	Max Utilization	Max Compression (kN.)
SCR ULS-Near = 0 m	2.86	1363
30	2.04	1191
75	2.06	1178
120	1.68	930
180	1.64	914
225	1.74	986
300	1.81	1023
750	1.99	1147

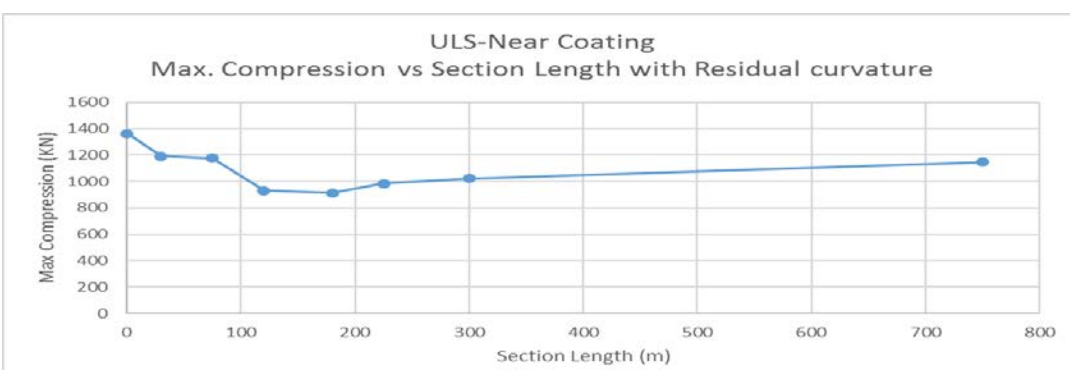


Figure 7. 20: Sensitivity for RC section Length - Max. Compression LC7, DV=4,27m/s

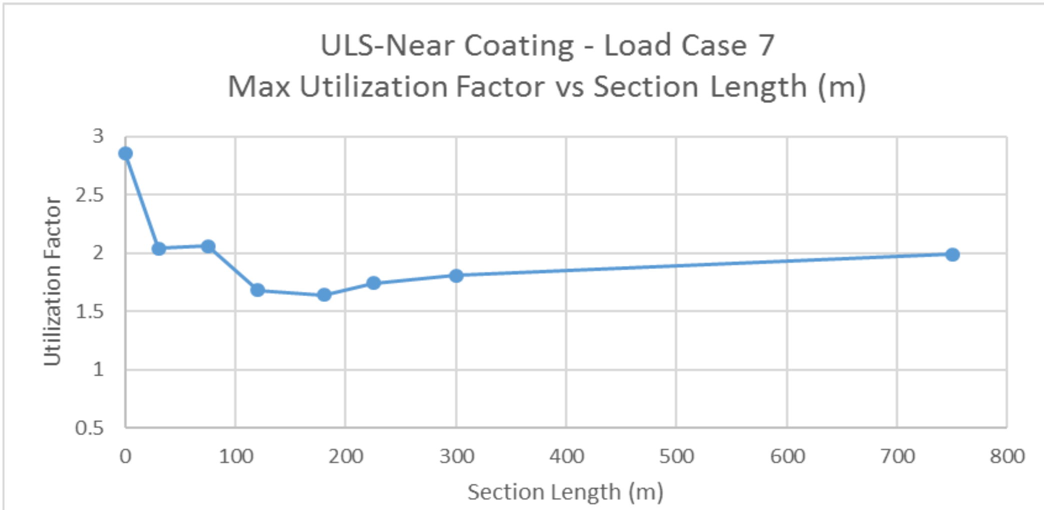


Figure 7. 21: Sensitivity for Section Length with RC, Utilization. LC7, DV=4,27m/s

From Figures 7.20 and 7.21, it can be seen that the lowest values for Utilization and maximum compression occurred when the section length reach 180m. With the conventional SCR the Utilization Factor is 2.86 for the load case used with a downward velocity at the hang-off point of 4.27m/s, by implementing the section with residual curvature, the utilization is reduced to 1,64. Similarly, the maximum compression is reduced from 1363KN for the conventional SCR to 914KN for the RCSCR with 180m of curvature section length.

Figure 7.22 illustrates the DNV utilization for SCR and variation of section length for the residual curvature section. The blue line describes the value of the utilization through the length of the conventional SCR in ULS-Near case. The other lines with different colors and dashes illustrate the utilization once the application for different section lengths is made on the SCR. It can be seen how once the application of the un-straightened section is made, the riser value for utilization in the sagbend is reduce, but the value for utilization where the section is applied increases.

Even though, the utilization factor is reduced when applied the residual curvature, the best case with 180m (red line) of section length does not enter in the acceptance criteria, obtaining a minimum UF value of 1.64.

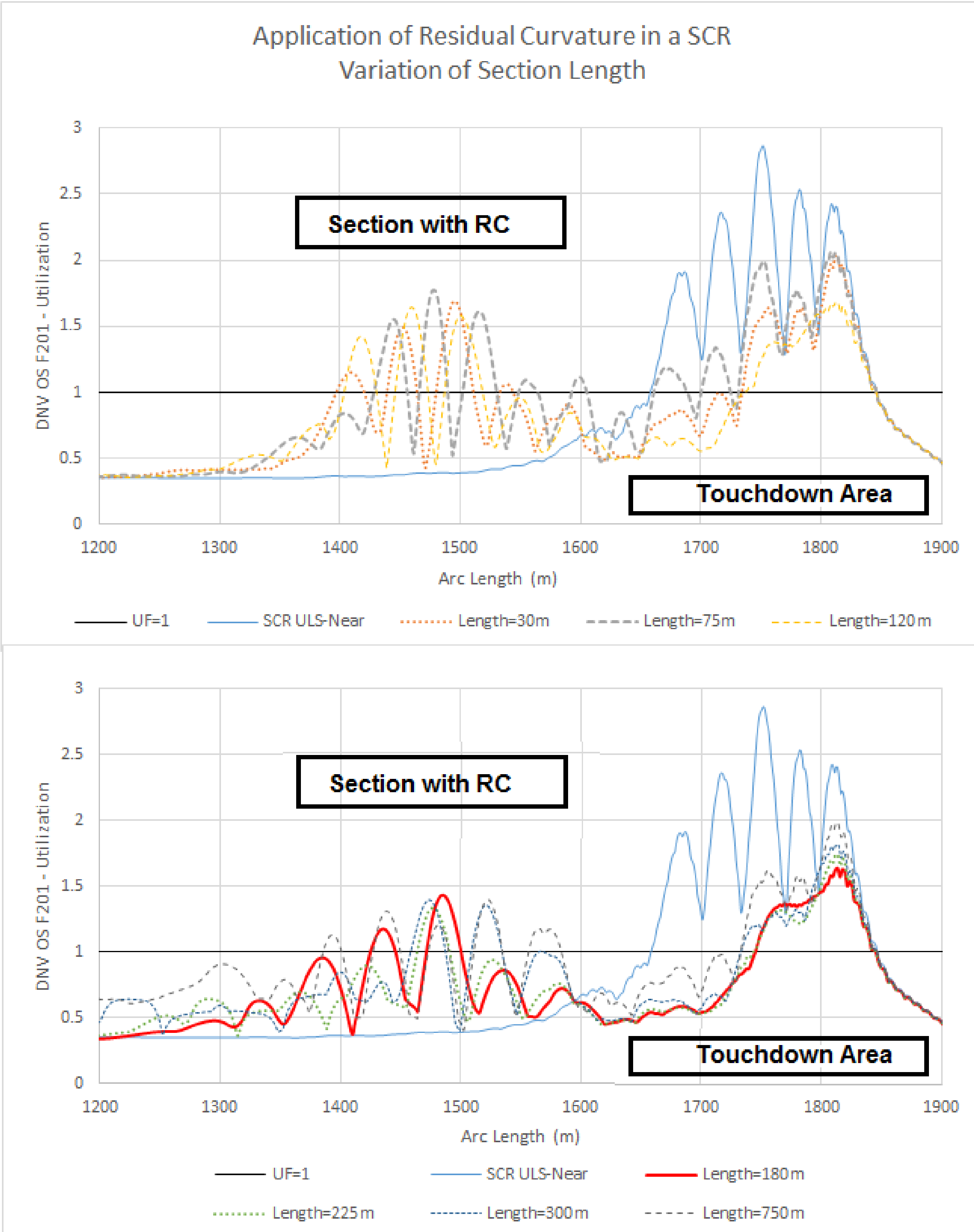


Figure 7. 22 Sensitivity for length in SCR with RC. RCSCR, LC7, DV=4,27m/s.

7.4.2 Sensitivity for Radius of Curvature

Table 7.12 shows the different radius of curvature used for the sensitivity analysis. In this case, the radius of curvature varies from 25m to 400m, and the conventional SCR. Radius of curvature are: 25, 50, 100, 140, 250 and 400 m and the corresponding curvature: 0.04, 0.02, 0.01, 0.007, 0.004, 0.0025 m^{-1}. This data is entering for the section length in OrcaFlex in the pre-bent option. All the four subsections in the section length will have the same curvature. The idea here is to study how the Radius of Curvature influence the utilization and the compression. This curvature is applied in OrcaFlex in the x-z plane for global coordinates and y-direction of the local coordinate system of the riser.

Table 7. 12: Sensitivity for Radius of Curvature. LC7, DV=4,27m/s

Radius of curvature (m)	Curvature (1/m)	Max UF	Max Compression (kN.)
SCR ULS-Near	0	2,86	1363
400	0,0025	1,87	1095
250	0,004	1,64	914
140	0,007	1,42	679
100	0,01	1,39	561
80	0,0125	1,36	508
50	0,02	1,76	391
25	0,04	3,06	188

According to Table 7.11 and Figure 7.23, for the SCR in ULS-Near configuration, the utilization factor is 2.86 and keep reducing while incrementing the amount of curvature in the section until it reaches an optimum point at 0.0125 m^{-1} which correspond to a radius of curvature of 80m with a utilization value of 1.36. However, if the curvature increases beyond this point the utilization also increases.

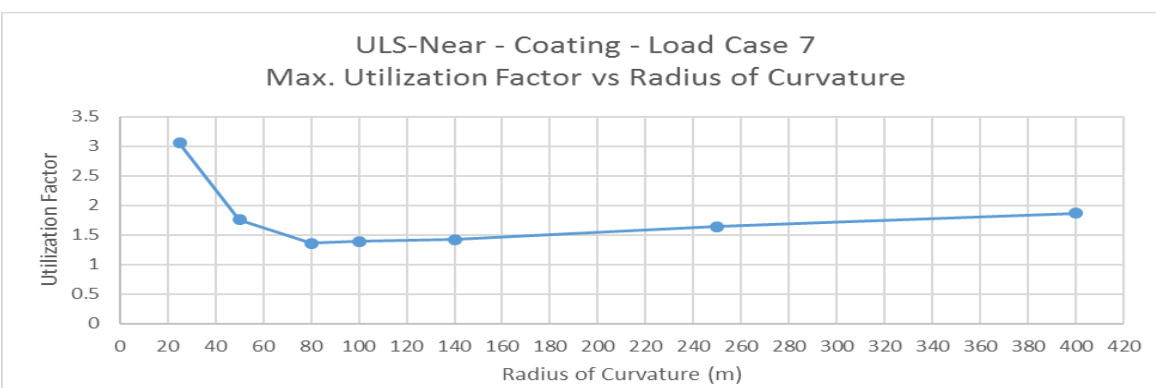


Figure 7. 23: Sensitivity for Radius of Curvature – Utilization. LC7, DV=4,27m/s

On the other hand, the increase in curvature will reduce the maximum compression, for SCR the maximum compression changes from 1363 kN to 188 kN with Radius of Curvature of 25m but the Utilization factor become higher that in the conventional SCR obtaining a value of 3.06.

Figure 7.24 illustrates the variation of radius of curvature in the un-straightened section. The blue line describes the value of the utilization through the length of the conventional SCR in ULS-Near case. It can be observed that the DNV utilization in the touchdown area of riser decreases with the increase in radius of curvature of the section with RC. With more curvature in the section, more reduction of utilization factor. However, in the area where the section is located the utilization increases. For example, for a radius of curvature 25m (brown dashed line), the utilization in TDP decreases from 2.89 with conventional SCR to almost one, but the utilization in the area where the section with RC is located increases dramatically reaching a value of 3.06. It can be observed in the line that the four subsections, each one with a different peak.

It can be concluded that even though the utilization decreases with more curvature, it reaches an optimum point where the utilization in the area where the section is applied becomes higher than in the TDP. As it happened when the radius of curvature is equal to 80m (Red line). In this value of curvature, the utilization in the touchdown area and in the area where the section is applied have almost the same value.

The residual curvature section impacts the utilization factor not only reducing its value but also moving the maximum utilization where the section with curvature is applied. This shows that Residual Curvature Method can be applied but the utilization due to its application should not affect negatively the riser integrity.

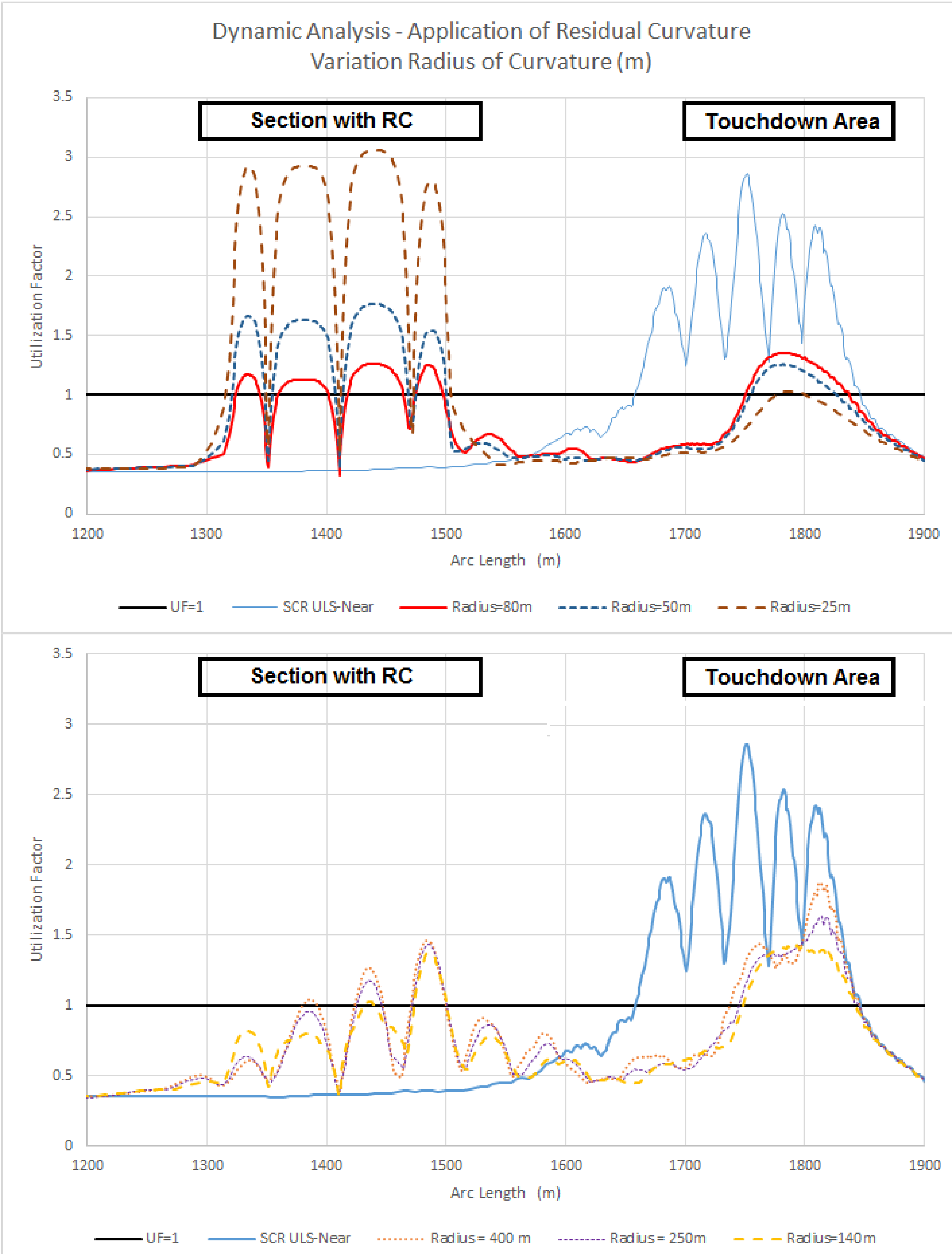


Figure 7. 24: Sensitivity for Radius of Curvature. LC7, DV=4,27m/s.

7.4.3 Sensitivity for Distance from Seabed

The idea in this analysis is to know an optimum location of the section along the riser. Figure 7.25 illustrates the parameter "distance from seabed", it is considered as the vertical distance from seabed to the lowest part of the section with curvature.

Figure 7. 25: Illustration of parameter distance from seabed to RC section
(No real curvature in section)

Table 7.13 show the values for sensitivity in relation to the distance from seabed in which the section with residual curvature is applied. Different distances are used varying from 1200m up in the riser near to the Semi, to 12 down near the seabed.

Table 7. 13. Sensitivity for distance to seabed. LC7, DV=4,27m/s

Arc Length (m)	Distance seabed in static near position of SCR (m)	Max UF	Max Compression (kN)
SCR Static ULS-Near	N/A	2,86	1363
295	1200	2,88	1328
1043	500	2,17	1125
1501	135	1,36	508
1653	50	1,34	330
1683	35	1,31	303
1715	25	1,42	267
1762	12	1,63	266

Figure 7.26 depicts how the as the distance from seabed is shorter the Utilization factor is reduced but until it reaches an optimum point where it stops reducing. For this sensitivity analysis, the utilization changes from 2.86 in the conventional SCR to a minimum of 1.31 for the RCSCR with the section distance to seabed equal to 35m, taking as reference the arc length of SCR in ULS-Near. For mean position of the RCSCR, this value is 72m.

On the other hand, the maximum compression decreases the closer the section approaches to the bottom. Starting from 1363 kN in the conventional SCR to 266kN.

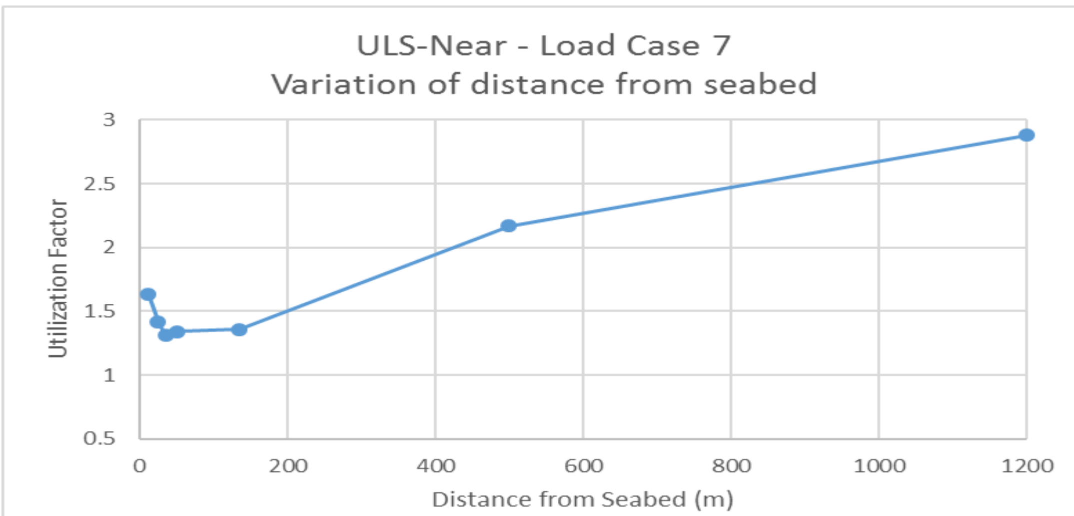


Figure 7. 26: Sensitivity for distance to seabed, Utilization. LC7, DV=4,27m/s

Figure 7.24 illustrates the variation of distance from Seabed of the un-straightened section. The blue line describes the value of the utilization through the length of the conventional SCR in ULS-Near case.

It can be seen that the utilization factor in the touchdown area of riser decreases with the increase in radius of curvature of the section with RC. The distance with value 35m (red line) have effectible reduce the UF of the riser to 1.31.

The influence of applying the residual curvature section up nearer the hang-off point is minimum for the value of utilization in the touchdown area. The closer the residual is applied to the seabed influence more to reduce the utilization, however, as mentioned before, there is an optimum point that the utilization start to increase.

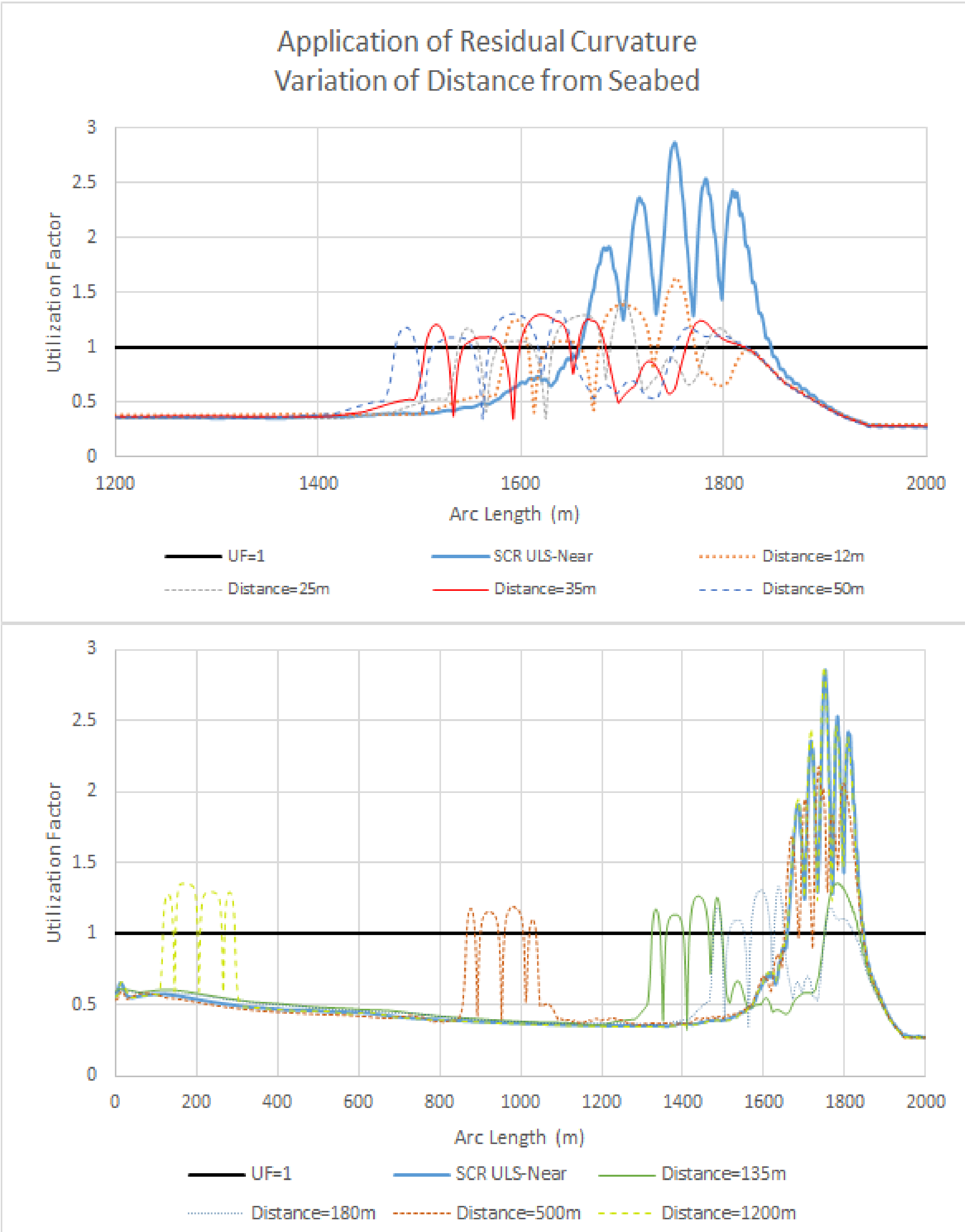


Figure 7. 27: Sensitivity for distance to seabed. LC7, DV=4,27m/s

7.4.4 Sensitivity for number of sections in row

So far, the section with residual curvature has reach the lowest utilization with the following values:

- Un-straightened section length = 180 m (30m, 60m, 60m, 30m)
- Radius of curvature = 80m, which indicates a curvature of $0.0125m^{-1}$
- Optimum distance from seabed for the lowest part of the section = 35m

In this case, the sensitivity will change the parameter "number of cycles or sections in row" with the same curvature and length applied to the riser. Figure 7.28 illustrates how the different sections with residual curvature will be applied along the line. Starting from the most optimum section that gives the lowest UF up to 35m from seabed.

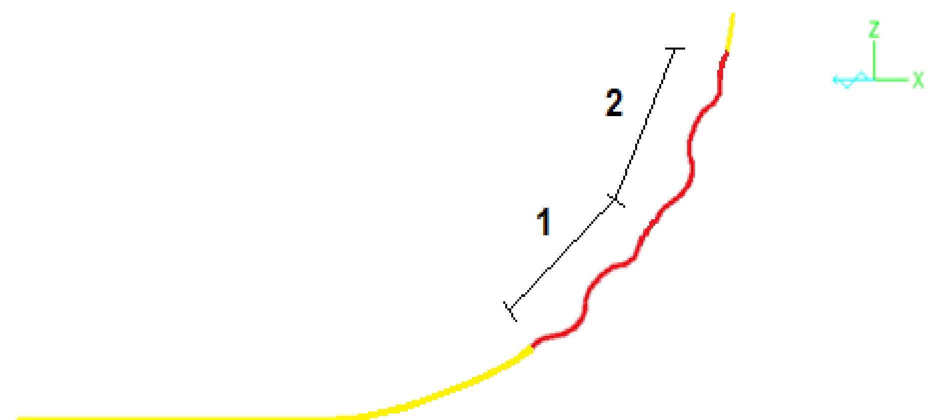


Figure 7. 28: Illustration of two RC sections applied in row
(No real curvature in section)

From Figure 7.29, can be seen that the application of more than one section do not reduce further the maximum utilization in the touchdown area. With a single section applied (red line), the utilization reaches the lowest UF. With two section applied in row (right-upper in figure 7.29), the changes in the value for utilization remain almost the same as with a single section. The more sections applied up along the riser do not reduce the utilization. For example, with four sections with residual curvature (down-right in figure 7.29), the value for utilization does not reach a lower value than the one given by a single section. Is it possible to say that for a SCR, there is a critical location where the application of residual curvature impact greatly the utilization at the touchdown area and the riser completely.

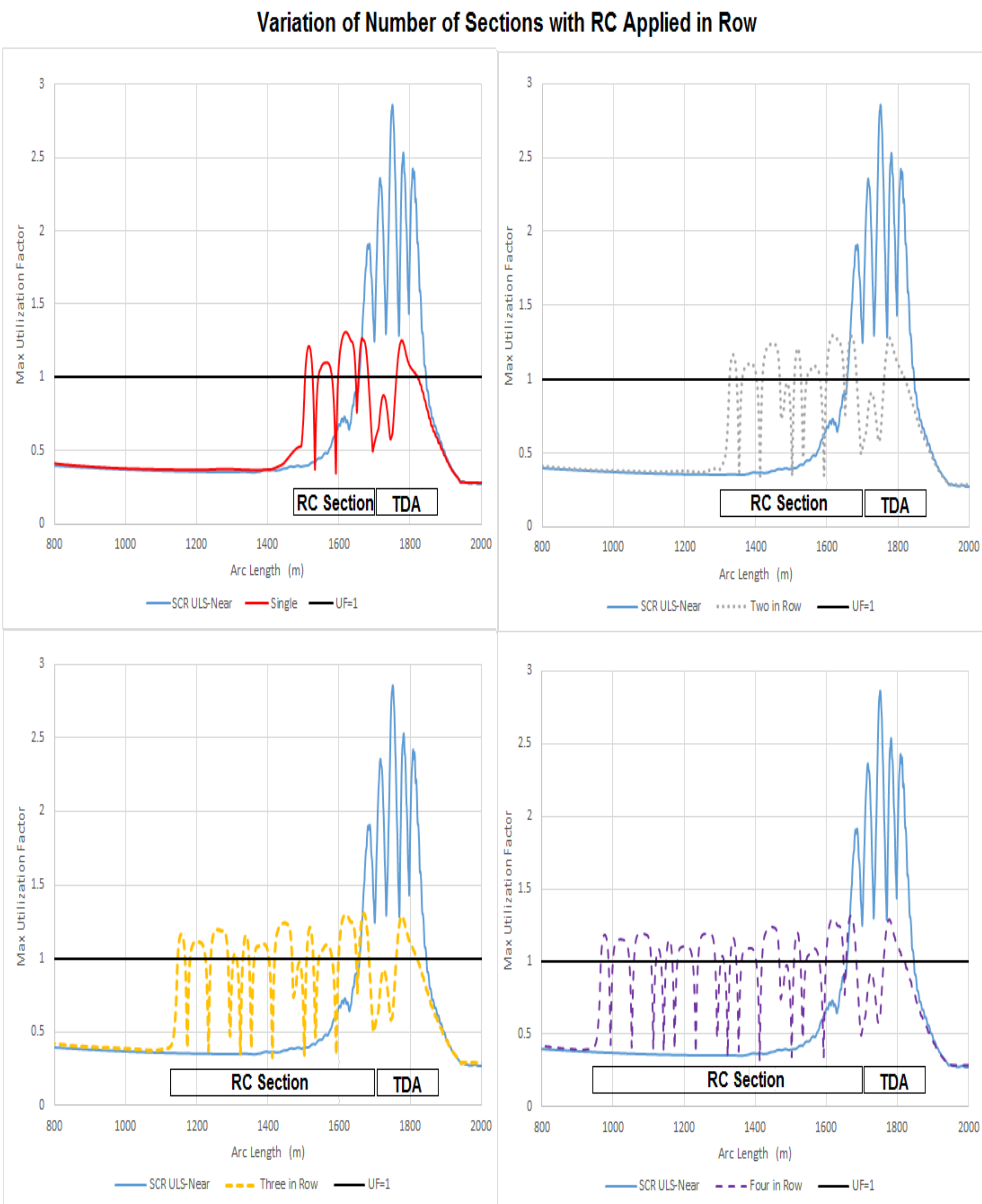


Figure 7. 29. Sensitivity for number of sections applied in row. LC7, DV=4,27m/s.

7.4.5 Sensitivity for two sections applied in different locations

In this sensitive analysis, the parameter to be changed is the number of sections implemented in different locations, having one section in the original place after the study made in chapter 7.4.3 (Sensitivity for Distance from Seabed) and the second one will be moved up through the riser arc-length, changing in distance from 100m, 200m, 300m and 1000m up. Both sections are applied with the same amount of curvature and length (as found in chapter 7.4.1 and 7.4.1). Figure 7.30 shows the application of the two sections, one in the original location found so far in this parametric study and the second 1000m up of separation through the arc length of the riser.

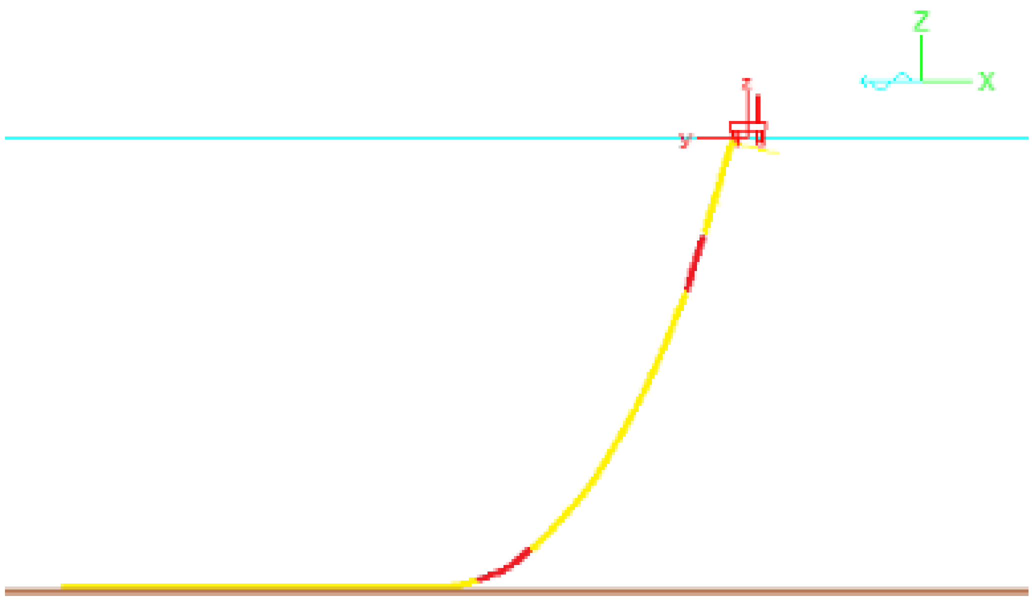


Figure 7. 30: Illustration of two sections applied in different locations.

From Figure 7.31, it can be seen that the application of a second section of residual curvature for any location does not reduce further the utilization at the touchdown point in comparison with applying a single section (Red line). For example, in the lower part to right in the figure 7.31, the second section is applied 1000m up along the riser nearer to the hang-off point. The impact of this second section is adverse and the value for the utilization factor slightly increases. Application of sections with residual curvature near the hang-off point do not affect positively the value of the utilization at the TPD.

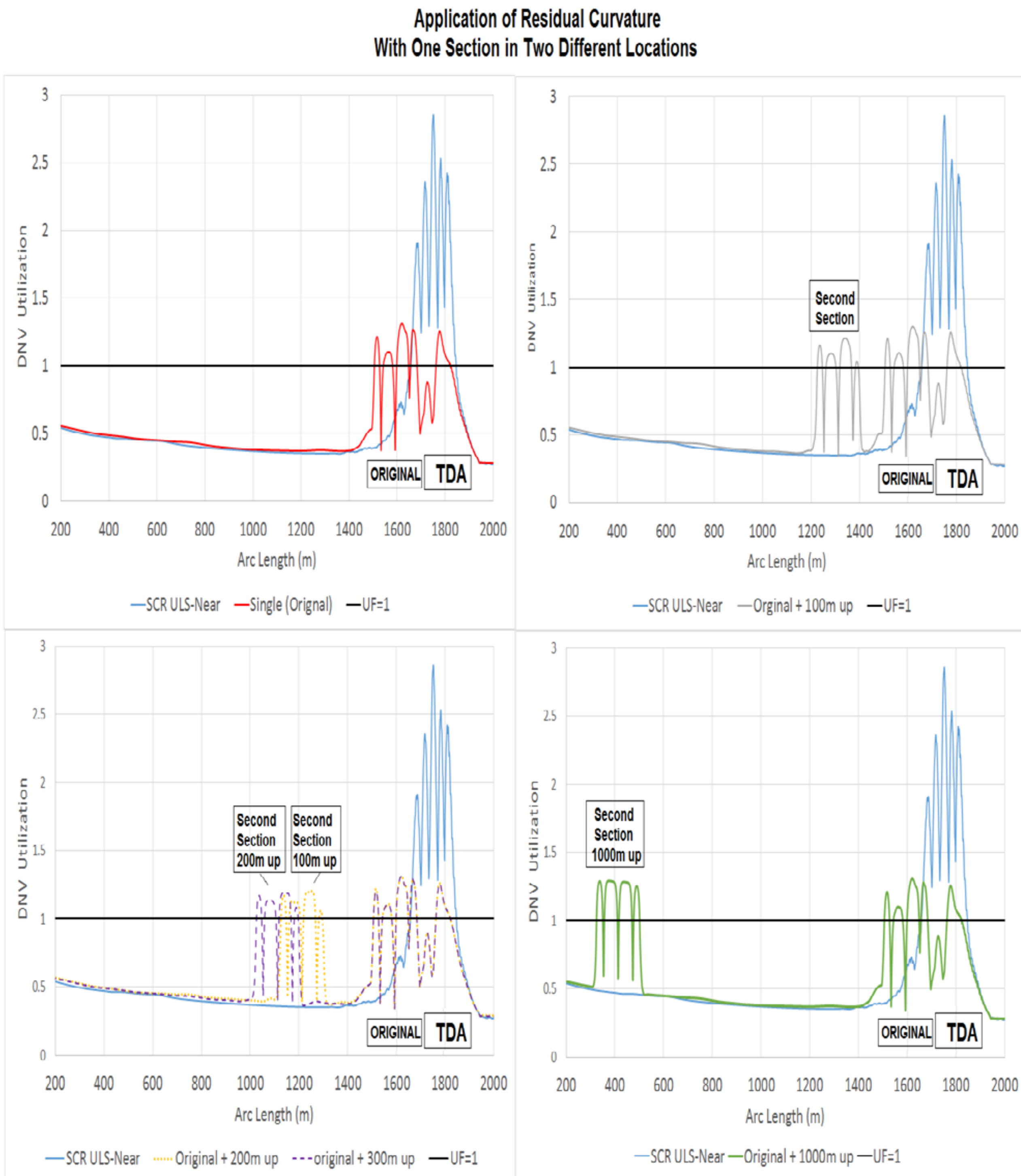


Figure 7. 31: Sensitivity for two sections applied in different locations. LC7

7.5 Preliminary Response Analysis for selected RCSCR

So far, the configuration of the section with residual curvature after the sensitivity analysis for the RCSCR that reduces in the best way the utilization along the riser is:

- Length of section = 180m (30m, 60m, 60m, 30m)
- Curvature = 0,0125 m^{-1}; Radius of curvature = 80 m
- Single section
- Distance from seabed in static for near Position= 35m

This configuration reduces the utilization of a SCR from 2.86 to 1.31 in the RCSCR. The sensitivity study was made for the 3h-sea state in hurricane condition which give a downward velocity of 4.27m/s in the hang-off point.

Table 7.14 shows the summary of strength response when load case 7 is applied in the RCSCR, the most critical configuration of load case is in ULS-Near with coating, the same for SCR.

Table 7. 14. RCSCR Strength Response Summary LC=7, DV=4.27m/s

Load case 7, DV=4.27m/s Full	Intact ULS		Damage ALS	
	Near	Far	Near	Far
Max. Effective top Tension (kN)	7483	9882	6984	10162
Max. Compression (kN)	303	394	279	426
Max. Bending Moment (kN.m)	1269	1162	1247	1174
Max. DNV LRFD Utilization	1,31	1,29	1,16	1,16

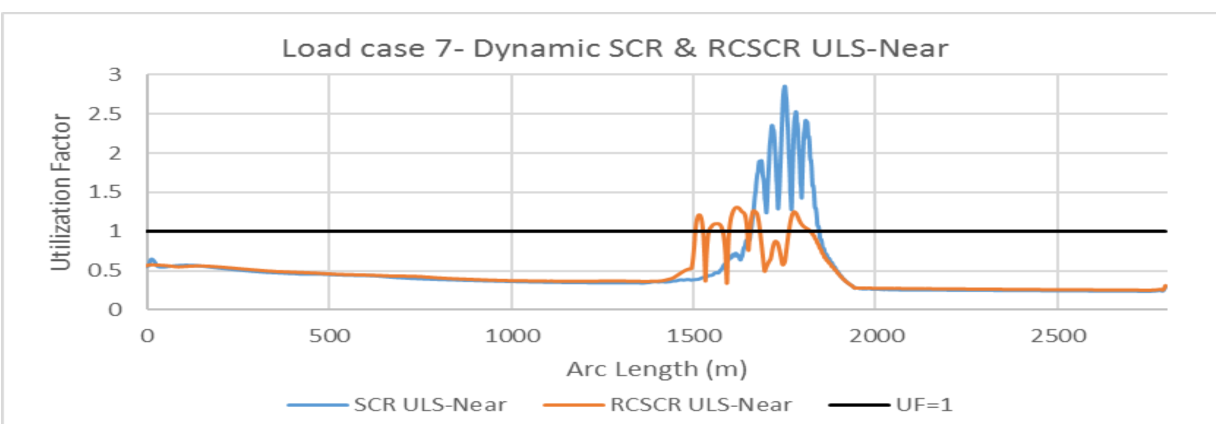


Figure 7. 32. Utilization for SCR and RCSCR, LC=7, DV=4.27m/s

From figure 7.32, it can be seen that the utilization is less in the RCSCR comparing with SCR in the touchdown area. However, for this load case, the utilization is still above the allowable value (UF>1).

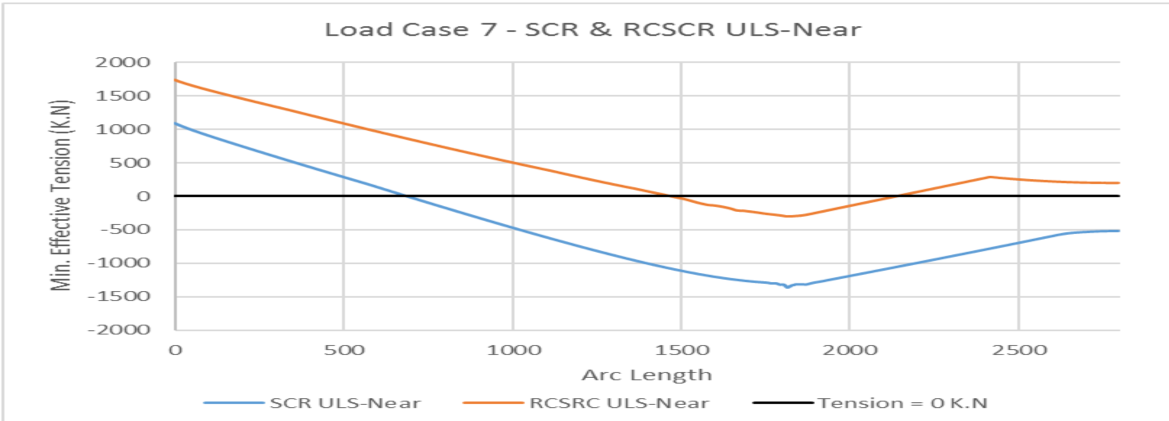


Figure 7. 33. Minimum Effective Tension for SCR and RCSCR.LC=7, DV=4.27m/s

According to Figure 7.33, the application of RC reduces substantially the amount of maximum compression in the riser. Likewise, the segment of the riser that works in compression is reduced. The RCSCR configuration is a feasible solution for the problem of compression in SCR. This was mentioned by Ramiro, 2018; in RCSCR configuration, the riser region that is in compression is reduced dramatically to acceptable values, this reduction is due to the mitigation of the loads along the riser due to the present of the un-straightened section in the RCSCR. The section tend to behave like a spring, which impact the local rigidity of the riser and therefore the propagation of the compressive forces along the riser (Ramiro, 2018).

To continue the analysis, the following procedure for the selection of the most optimum RCSCR is implemented. Considering step 5, the idea is to find the RCSCR configuration that bring maximum downward velocity which the riser can work when checking the utilization factor be under the allowable value (UF<1). For this, it is necessary to use a load case that give as a result a lower value of maximum downward velocity at hang-off point.

With load case 5, which have a maximum downward velocity of 2.94m/s at the hang-off point, it will be analyzed to check the maximum utilization and compression. Table 7.15 shows the summary for the strength response for the chosen load case. It can be seen that the Utilization factor is still over the allowable value and that the most critical configuration is for the ULS-Near. Only coating is shown as has been proven that without coating the utilization is lower.

Table 7. 15: RCSCR Strength Response Summary LC=5, DV=2.94m/s

Load case 5 Full	**Intact ULS**		**Damage ALS**	
	Near	**Far**	**Near**	**Far**
Max. Effective top Tension (kN)	5866	7068	5568	7272
Max. Compression (kN)	83	83	83	83
Max. Bending Moment (kN.m)	1174	1083	1206	1080
Max. DNV LRFD Utilization	1,18	1,19	1,10	1,09

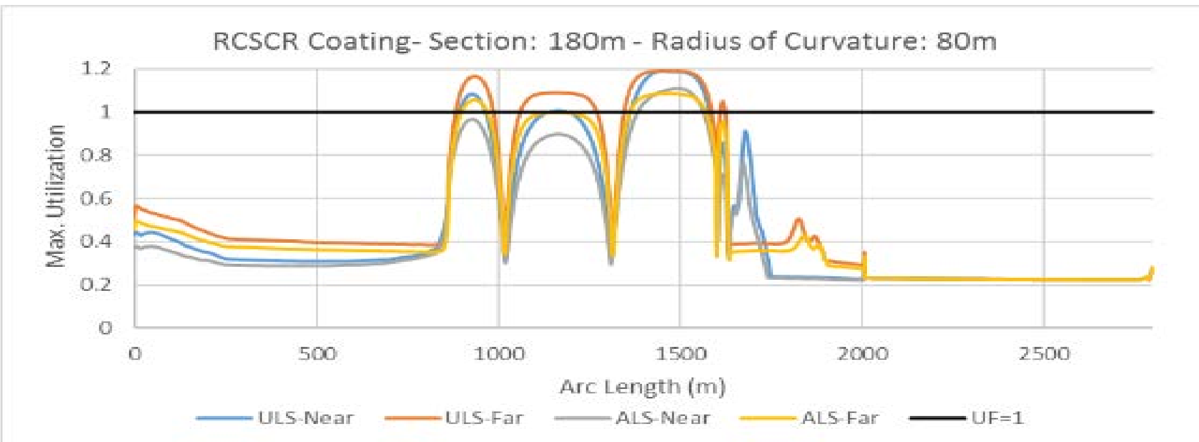


Figure 7. 34. Utilization for RCSCR, LC=5, DV=2.94m/s

From Figure 7.34, it can be seen that the utilization is over the allowable values in the segment of the riser where the section with RC is applied. However, the utilization in the touch down area is fully reduce and is less than one for all the offsets and limit states.

The curvature increases the utilization factor where it is located. Them, there is a limit to which it can be apply when the utilization in the area near the touchdown gets lower than one.

"The Residual Curvature Method applied in a SCR helps to reduce stress by lowering the value of the utilization factor and reducing compressive forces; however, it is a self-limiting process"

Then, it would be necessary to re-design the section with residual curvature to maximized is implementation and obtained a maximum downward velocity that can cope satisfactory, obtaining a utilization less than one.

A fine-tuning process is made to implement the section using the load case 5, to obtain a section with residual curvature that perform under allowable value of utilization factor for the downward velocity of 2.94m/s. It has been established from the sensitivity analysis that the radius of curvature and the length in the section with RC impact the most in the improvement of the utilization. Starting with length of section equal 180m. It can be seen in Table 7.15 that when applying a radius of curvature of 111m, the utilization is reduced to 0.97, with this getting into the allowable value. This radius of curvature corresponds to a curvature of 0.009 m^{-1}.

Table 7. 16. Fine-tuning with Radius of Curvature of section length=180m

LC=5, DV=2.94m/s

Radius of curvature (m)	Curvature (1/m)	Max UF	Max Compression (kN)
SCR ULS-Near LC=5	0	1.21	369
125	0,008	1,12	146
111	0,009	0,97	125
80	0,0125	1,18	83

$R = 111m$ $\frac{1}{R} = \frac{0.009m^{-1}}{m} = \theta = k =$ Curvature

For ID10" SCR, the residual strain would be:

Strain; $\varepsilon = \frac{r}{R} = \frac{d}{2R}$

The relation between curvature and residual strain in the riser is:

$$\varepsilon = r * k = \left(\frac{d}{2}\right) * k \qquad \varepsilon = \left(\frac{0.332m}{2}\right) * 0.009m^{-1} = 0.0015$$

Obtaining a residual strain of 0.15%.

Likewise, fine-tuning process is made by checking is the length of 180m is still the most suitable. Table 7.16 shows the fine-tuning with the section length, but it does not improve the utilization factor when changing. Length =180 m is still the best option. Results for ULS-Near are shown.

Table 7. 17: Fine-tuning with length. LC=5, DV=2.94m/s

	Length (m)	Max UF	Max Compression (kN.)
SCR ULS-Near LC=5	0	1,21	369
	225	0,98	131
	180	**0,97**	**125**
	150	0,99	146

7.6 Revision of Selected RCSCR Configuration Static State

In this section, static analysis is made on the selected RCSCR configuration to confirm that it works according to DNV standards, considering the parameters found on the sensitivity analysis and fine-tuning:

- Same riser arc length as used for the SCR= 2796.3 m
- Length of curvature L= 180 m, (30m, 60m, 60m, 30)
- Curvature: 0,009 m^{-1}, Radius of Curvature: 111m
- Single section with residual curvature,
- Applied to 35m over the seabed in mean position (SCR arc length as reference).

Table 7. 18: RCSCR static results – Full– Functional loads only

RCSCR Static Full ULS	Near	Mean	Far
Hang off Angle (°)	15,5	16,8	22,1
Effective top Tension (kN)	3980	4364	4713
Max. Bending Moment (kN.m)	825	803	790
Max. DNV LRFD Utilization	0,88	0,87	0,87

According to Table 7.18 and figure 7.35, the value for utilization is less than one and there is not compression along the riser for any of the locations, the biggest tension is for the far offset. The effective tension is higher along the riser in far offset and lower for Near offset. Comparing the results with SCR (table 7.4), there is a variation of top angle with the same length of the riser (2796.3m), having 15° in the SCR and 16,8 in the RCSCR in mean static position. Likewise, there is a reduction in effective top tension for RCSCR but an increase in the bending moment and utilization.

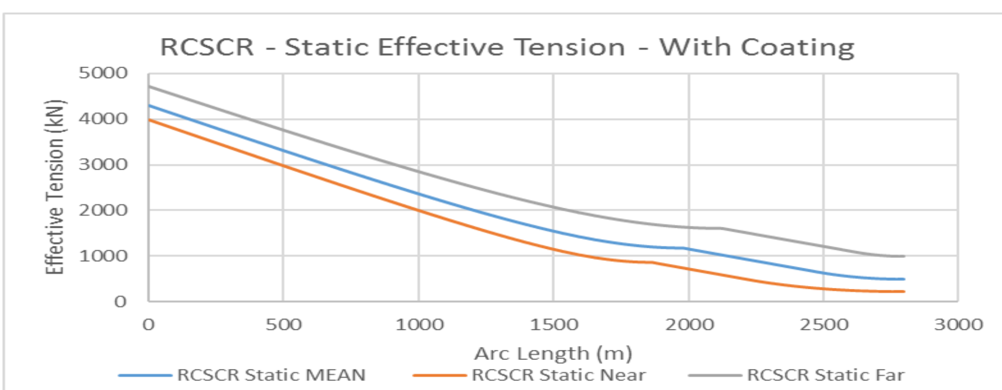


Figure 7. 35: RCSCR Static effective tension.

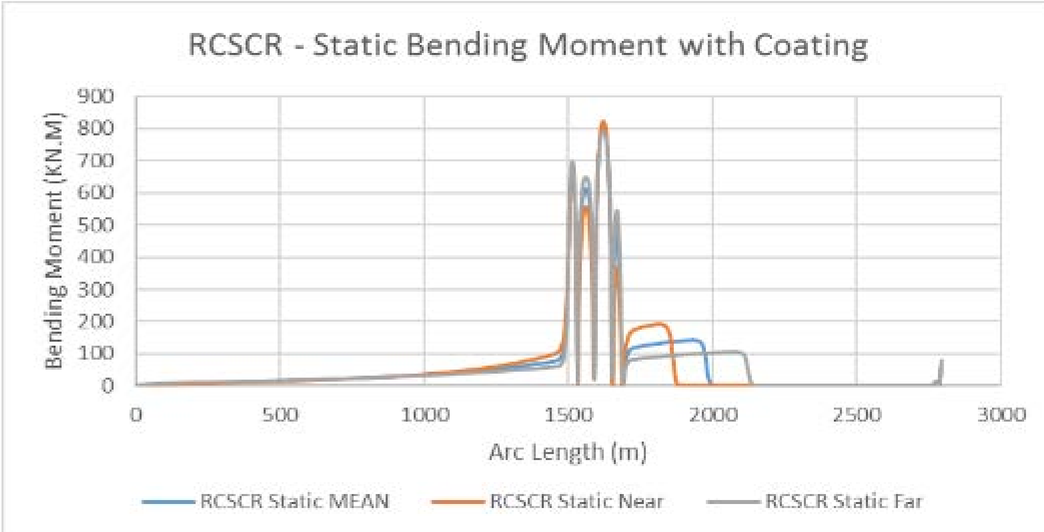


Figure 7. 36: RCSCR Static Bending Moment

From figure 7.36, the static bending moment shows a maximum where the section with residual curvature is applied.

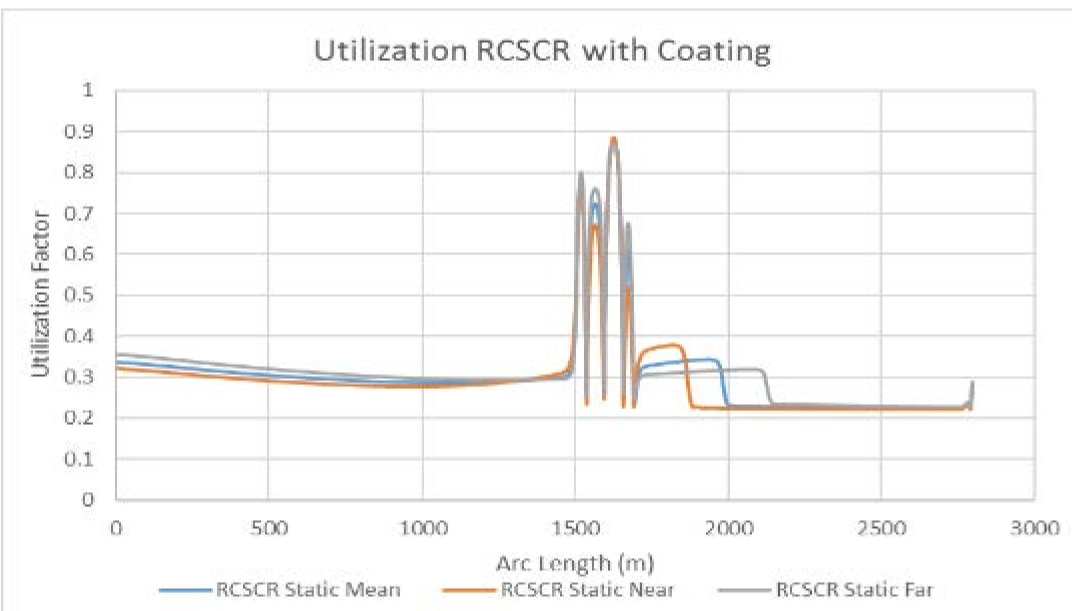


Figure 7. 37: RCSCR Utilization Factor

Figure 7.37 illustrates the differences in utilization factor for the RCSCR for Near, mean and Far offset, the maximum utilization occurred in the same location along the riser as the maximum value for the bending moment, indicating that when RC method applied, bending moment along the section with residual curvature become the critical response.

Comparing the curvature between in SCR and RCSCR for ULS-Mean offset, in figure 7.38, it shows that the maximum curvature occurred where the section with residual curvature was applied. Curvature, bending moment and utilization are directly related, when residual curvature is applied, then the RC becomes the design driver for the RCSCR configuration.

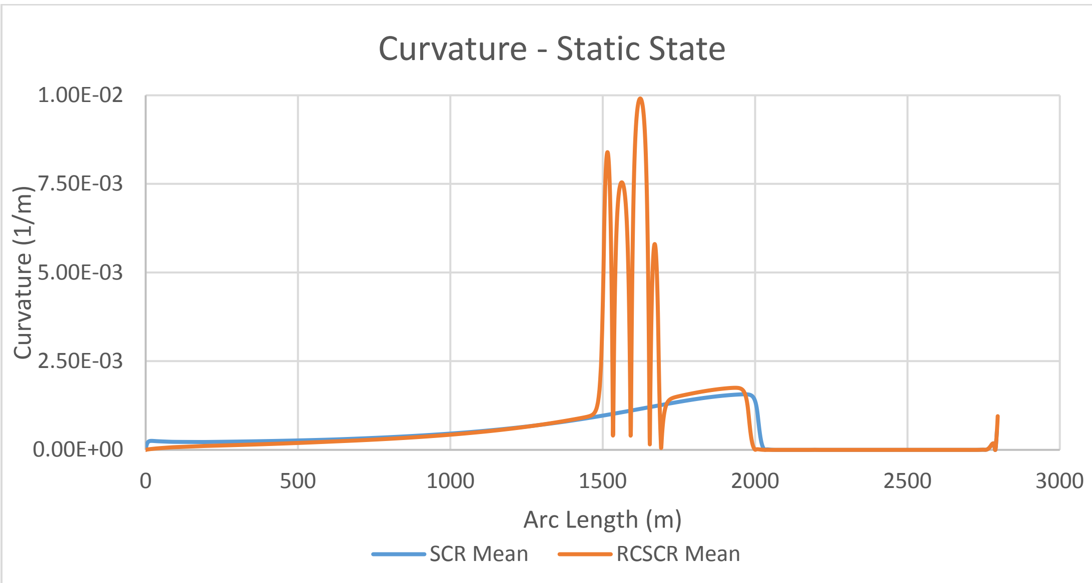


Figure 7. 38: Curvature along the riser for SCR & RCSCR Configurations

7.7 Top Angle Variation on selected RCSCR configuration

The initial SCR in static and mean position have 15° (Table 7.4) at the top angle relative to the vertical in the hang-off point as require by design. After the application of the residual curvature section, increase of segments or nodes in the line and keeping the length of the riser in the same value of 2796,3m, the angle for the riser in RCSCR changed to 16,8° in static mean position.

In this chapter the influence of the changes in the top angle is studied in relation to the maximum effective tension at the top and the utilization factor. Load case 5 will be used in this analysis and the option of "Line Setup wizard" in OrcaFlex to fix the angle required. The current profile will not be taken into account as the analysis is made in mean position for the platform.

Table 7. 19. Variation of top angle with RCSCR. LC=5, DV=2.94m/s

RCSCR Mean LC5	**Top angle**			
	10°	**15°**	**16,8°**	**25°**
Line length (Using line setup wizard)	2960	2834,7	2796,3	2644,2
Max. Top tension	5401	6217	6419	8004
Max Utilization at Hang-off point	0,4	0,46	0,46	0,60
Max Utilization	1,05	0,97	0,98	0,98

From Table 7.19 can be extracted that the maximum top tension increases with the value of the top angle. In the same way happen with the maximum utilization factor. The configuration with top angle equal 10° shows an excess of maximum utilization along the riser, while the value for 15°, 16.8° and 25° is similar.

Likewise, Figure 7.39 illustrates the utilization for different top angles. The Utilization remain under the allowable value for 15°, 16.8° and 25°. However, for 10° exceed UF. It can be observed that for 25° the top maximum UF is higher.

The dynamic analysis and comparison with other riser configurations will continue with the top angle value of 16.8° for the RCSCR as the variation in result for the Utilization factor differs from 15° in less than 1%, having as a result 0.97 for the 15° and 0.98 for the 16.8° top angle. The idea of this this work is to study the application of residual curvature on free hanging risers, and for the time constraint give to this studied, it was decided to do the sensitivity analysis taken in consideration the same arc-length of the SCR for the application of the sections to the RCSCR, saving time in re-calculating different arc-length for the risers every time a different un-straightened section was applied.

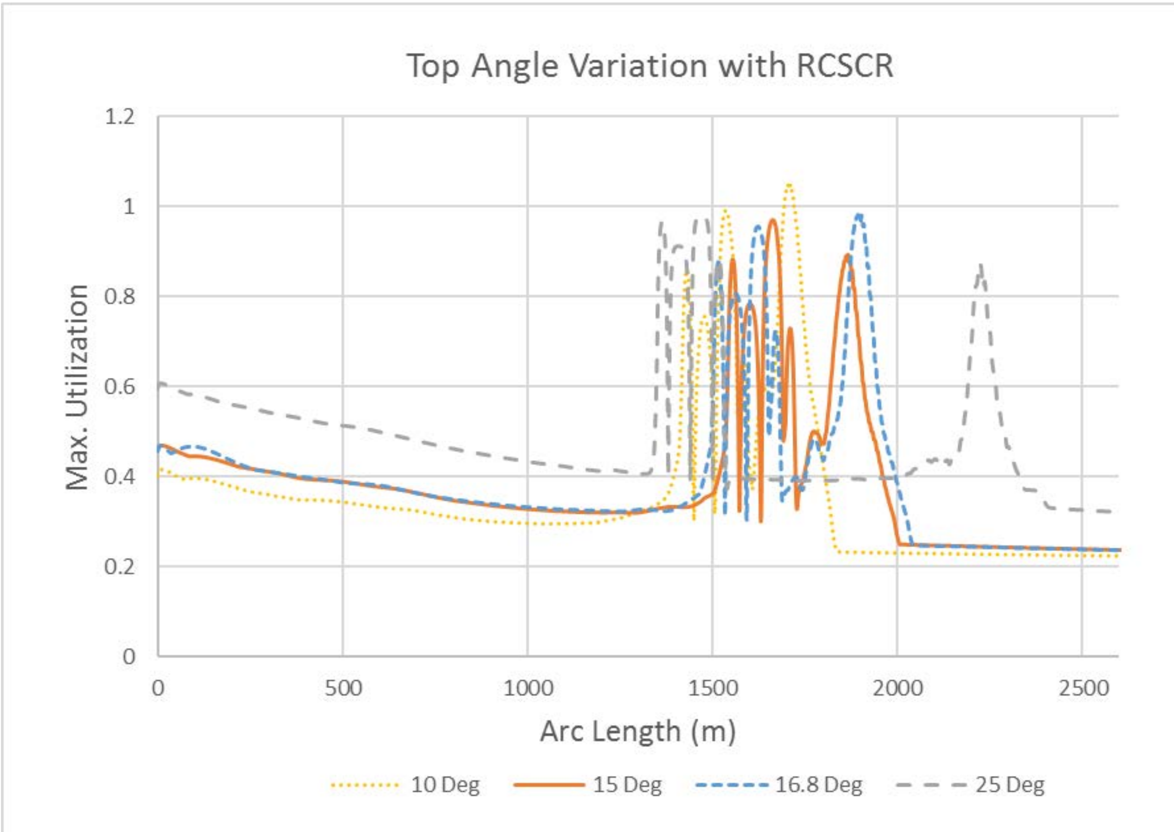


Figure 7. 39. Variation of Top Angle and effect on Utilization for RCSCR

7.8 Dynamic analysis for the selected RCSCR configuration

In this section, dynamic analysis is made on the selected RCSCR configuration to confirm that it works according to DNV standards, considering the values found on the parametric study and fine-tuning:

- Same riser arc length as used for the SCR= 2796.3 m
- Top angle: 16,8° in mean position (Table 7.19 shows negligible difference in value for maximum utilization at Hang-off point and along the riser as a top angle of value 15°)
- Length of curvature L= 180 m, (30m, 60m, 60m, 30)
- Curvature: 0,009 m^{-1}, Radius of Curvature: 111m
- Single section with residual curvature,
- Applied to 35m over the seabed in mean position (SCR arc length as reference).

Only ULS-Near case is analyzed and the selected RCSCR.

Tables 7.2 to 7.22 shows the results for the RCSCR strength response for different downward velocities. It can be observed that the RCSCR work perfectly for 2.64 m/s, Same velocity as the SCR start to fail. Then, RCSCR fails at a higher velocity start to fail at higher velocity as seen in Table 7.21 with a downward velocity of 2.94 m/s and a Utilization Factor of 1.13. Even though the improvement in capacity for the RCSCR in relation to the SCR is small (around 10%). This shows that the application of the Residual Curvature Method enhance the ability of a SCR to handle higher stress loads. As a result can manage higher downward velocity at the hang-off point. The un-straightened section improve the value of the utilization for the SCR.

Table 7. 20: RCSCR Strength Response ULS, LC=5, DV=2.94m/s

Load case 5, DV=2.94 m/s Full	**Semi**	
	Intact ULS	
	Near	**Far**
Max. Effective top Tension (kN)	5814	7074
Max. Compression (kN)	125	0
Max. Bending Moment (kN.m)	899	795
Max. DNV LRFD Utilization	0,97	0,97

Table 7. 21: RCSCR Strength Response ULS, LC=6, DV=3.31m/s

Load case 6, DV=3.31 m/s Full	**Semi**	
	Intact ULS	
	Near	**Far**
Max. Effective top Tension (kN)	6262	6989
Max. Compression (kN)	255	0
Max. Bending Moment (kN.m)	986	803
Max. DNV LRFD Utilization	1,13	0,97

Table 7. 22: RCSCR Strength Response ULS, LC=7, DV=4.27m/s

Load case 7, DV=4.27 m/s Full	**Semi**	
	Intact ULS	
	Near	**Far**
Max. Effective top Tension (kN)	7588	9821
Max. Compression (kN)	387	577
Max. Bending Moment (kN.m)	1249	876
Max. DNV LRFD Utilization	1,35	1,06

For example, comparing Table 7.22 and the value obtained in Utilization for the same load case (LC 7 in USL-Near position) applied to the SCR. The RCSCR obtained a reduction to 1.35 from 2.89 in the SCR configuration.

After this analysis, it can be observed that the RCSCR configuration perform better than the SCR. According to Ramiro and also validated in this study; the un-straightened section tends to behave like a spring, which affect the local rigidity of the riser and thus the propagation of compressive forces. For the RCSCR, the regions in compression are reduce dramatically, the section with residual curvature mitigates the propagation along the RCSCR (Ramiro, 2018).

It can be concluded after this analysis that:

RCSCR $<$ 2.94 m/s ---- Utilization <1

Figure 7.40 presents the results for the different riser configurations in ULS-Near and dynamic analysis. SCR, WDSCR and RCSCR are compared in relation with the DNV utilization and the downward velocities at the hang-off point. The SCR has the lowest performance, the allowable value (UF=1) which the SCR can perform without problem is under 2.65 m/s. On the other hand, WDSCR configuration perform up to 3.2 m/s. Finally, for the RCSCR, the restriction for the downward velocity is 2.94 m/s. This new riser configuration has a performance in between the SCR and the WDSCR. From the Figure, it is worth mentioning that RCSCR has higher DNV Utilization for lower downward velocities in relations to the other two free hanging riser configurations. This is an important issue to be considered.

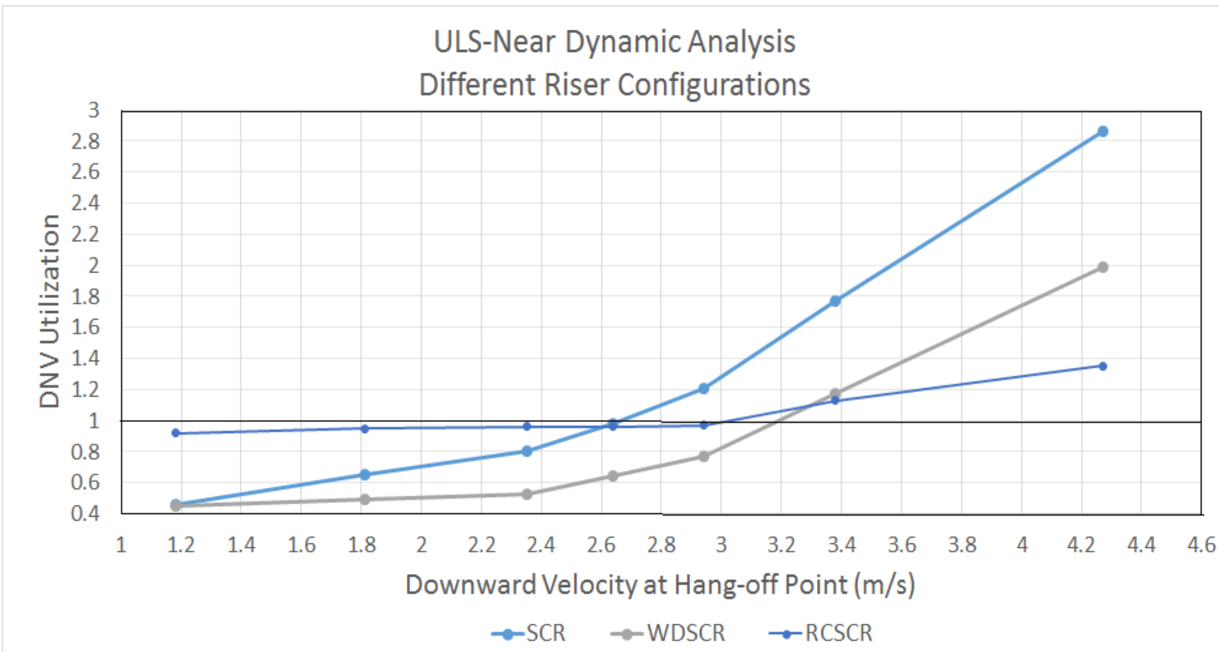


Figure 7. 40. Utilization vs Maximum Downward Velocity at Hang-Off point

Following this investigation of the merits and challenges for the RCSCR. To handle with load case 7, which describes a 3-h sea state under hurricane condition that gives a downward velocity of 4.27m/s at the hang-off point for the selected Semi-Submersible, and knowing that RCSCR can only handle with downward velocity of 2.94m/s. Likewise, noticing that the selected WDSCR can also cope with 3.2m/s. The idea is to apply RC to the WDSCR and check the results.

Figure 7.41 illustrates the section with residual curvature and Weight Distributed section on a SCR. The RC section is applied between the WD section and the TDP.

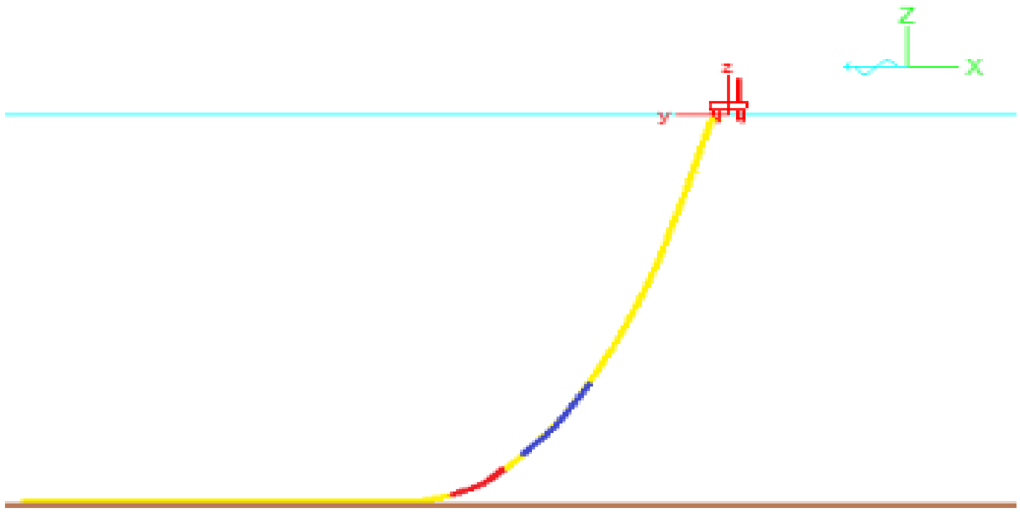


Figure 7. 41. Residual Curvature section and Weight Distributed section on a SCR

From figure 7.42, it can be observed that even though the RC-WDSCR configuration obtained in general the lowest value for the utilization comparing with SCR, WDSCR and RCSCR, it was not able to handle a downward velocity of 4.27 m/s from LC7.

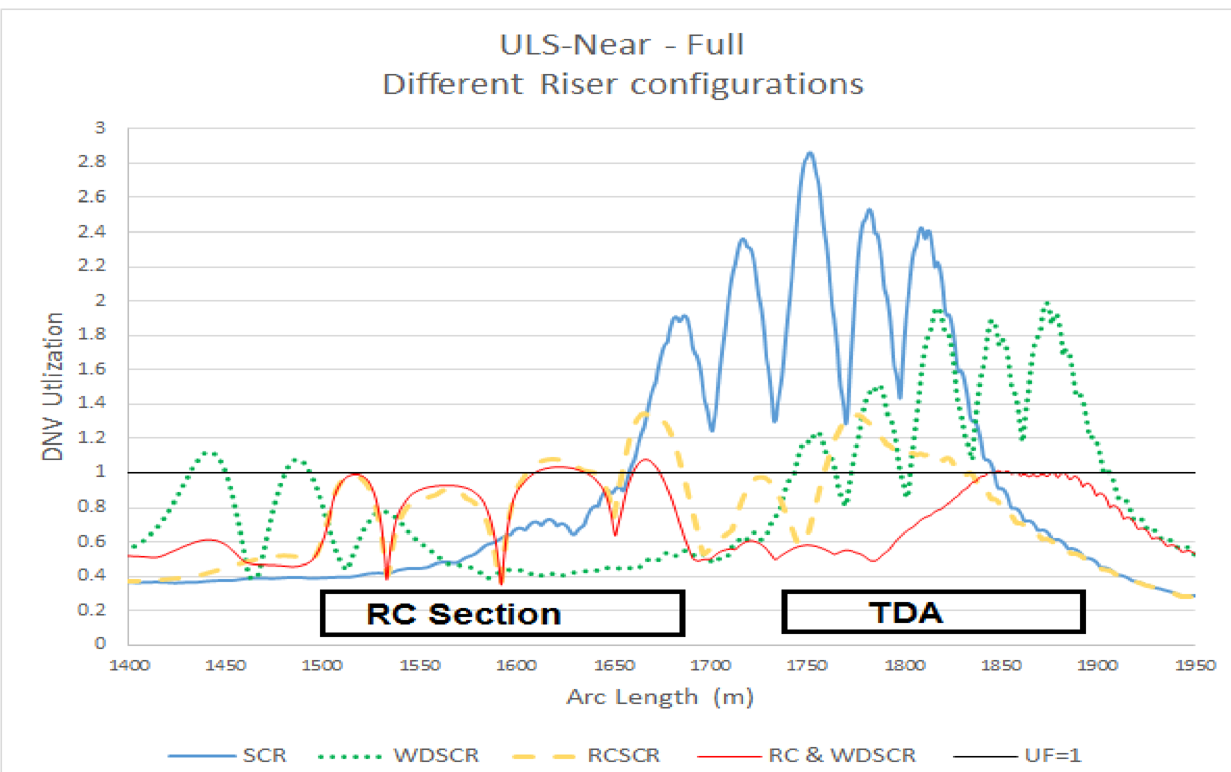


Figure 7. 42. Max Utilization for different Riser configurations. LC=7, DV=4.27m/s.

Using a different seed that gives maximum downward velocity of 4.01m/s, a utilization factor with a value of 0.99 is obtained as shown in Table 7.23.

Table 7. 23: Load case 8, Max Downward velocity =4.01m/s

Hs (s)	Tp (s)	Y	Downward Velocity at the hang-off (m/s)	Seed order "m"	Wave Seed for "m"
15,8	16,9	2,365	4,01	15	5258

Once applying the section with residual curvature (RC) and weight distributed (WD) on a SCR. The new riser configuration RC-WDSCR is able to cope with a maximum downward velocity of 4.01m/s (Figure 7.43). It can be observed the two critical location RC section where the un-straightened section has been applied and the touchdown area, the maximum utilization occurred at the location of the RC section. The RC section "absorb" or move away from the TDA the maximum load stress in the riser. With RCM on free hanging risers, there is a re-distribution of the stresses along the risers. The maximum utilization is reduced and re-located in the un-straightened section.

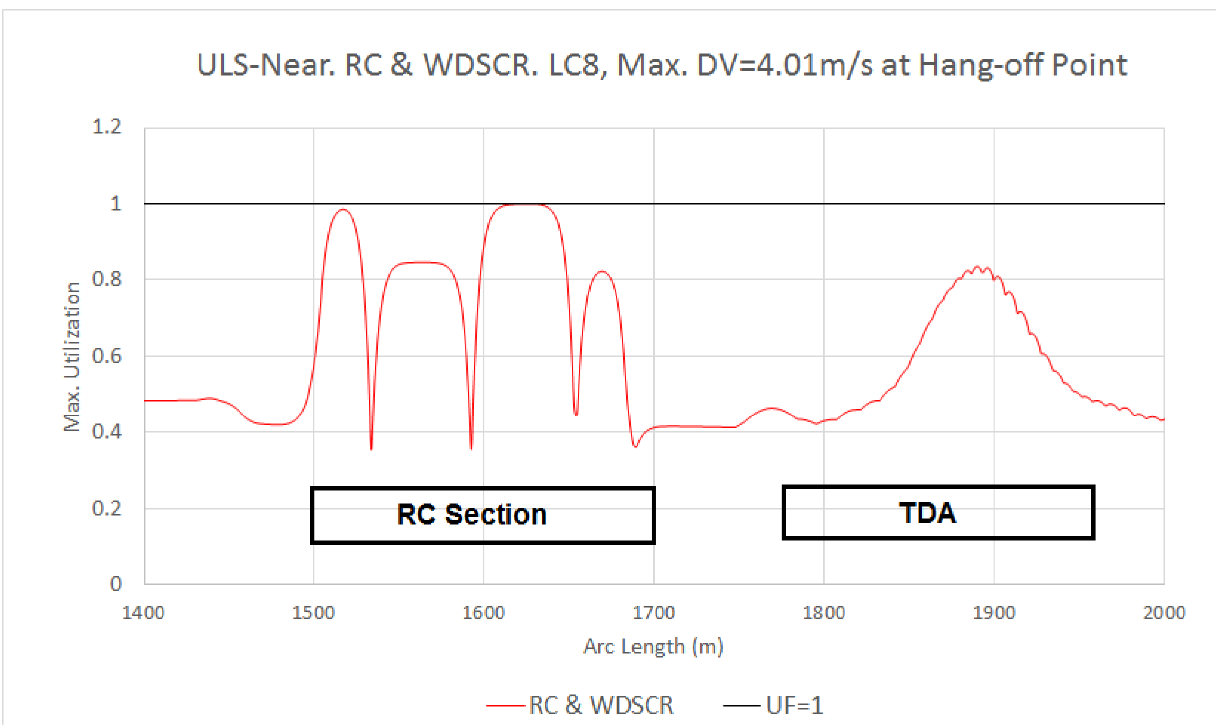


Figure 7. 43. Max utilization for the WDSCR with RC section configuration.

Summary for Extreme analysis:

Different free hanging steel catenary riser configurations were studied by screening the downward velocity that can be handled using the DNV-OS-F201 buckling utilization.

The conventional SCR is able to withstand with DV at the hang-off point of 2.64m/s. Then, after performing a parametric study of the geometry and location for the application of sections with residual curvature, it was found that the configuration with a single section of 0009m^{-1} of curvature, 180m of length and with a distance of 35m from the seabed achieved the most optimal reduction of the value of the utilization. The summary of the downward velocities each riser can cope is describe as follows:

- Selected conventional SCR = 2,64 m/s
- Selected RCSCR=2,94m/s
- Selected WDSCR= 3,2 m/s
- RC & Selected WDSCR=4.01 m/s

The Residual Curvature Method applied on a SCR reduces stress and reach a value for the downward velocity near to the WDSCR configuration. RCSCR can potentially replace the Weight Distributed section if it is necessary to cope with a downward velocity of 2.94m/s at the hang-off point, bringing close results in the ability to cope with a downward velocity as the WDSCR configuration. With this, saving costs by avoiding the installation or by reducing the number of heavy modules (ballasts) or the implementation of high-density coating sections used in the WDSCR riser configuration.

Likewise, residual curvature method can potentially improve the selected WDSCR configuration, increasing the downward velocity that can be handle.

Key observations on RCM for SCR (validation of results obtained by Ramiro, 2018):

- There is a critical section in the sagbend near the touchdown area where the application of residual curvature is more effective.
- The larger the radius of curvature, the greater the attenuation of compressive forces. However, the reduction of the maximum utilization stops at an optimum point and start to increase dramatically.
- The closer to the seabed, the greater the attenuation of the compressive forces generated by the floater motion. However, once an optimum point is reach, the reduction of the utilization stops and start to increase.

Chapter 8. Fatigue Analysis

8.1 Introduction

In relation to the upper end termination for the extreme condition analysis (chapter 6.5.3), the pin joint configuration was used to replace the flex joint (Table 6.8). Thus, in the extreme loading conditions, the top end is modeled as pinned with zero stiffness in bending and twisting. As mentioned before, the top end is modeled as pinned since the flex-joint stiffness will not affect the riser response in extreme loading conditions (Karunakaran et al., 2005). Having said that, for fatigue analysis the flex joint option is used considering the addition of stiffness of 20kN.m/deg in bending and twisting at the top end of the line (figure 6.3). In order to keep top angle 15° relative to the vertical and the same distance from the center of the platform to the anchor point (2000m) for both conventional SCR and selected RCSCR in chapter 7.5 in static mean position, it was necessary to re-run the line setup wizard to calculate the lines length. With this, the arc length for both SCR and RCSCR in static and mean position changed from 2796,3m to 2834.7m, this calculation was made in chapter 7.7 when analysis the changes in top angle. The current profile is not taking into account for the fatigue analysis.

As reported by DNV (2010a), fatigue damage is caused mainly by low frequency stress cycles, wave induced stress cycles and Vortex Induced Vibrations (VIV) stress cycles. According to Karunakaran et al, 2005, the most critical area for riser fatigue damage is at the welded joint connections near the TDP due to the complex interaction and pounding between the riser and the seabed.

In this thesis, only the study for wave induced fatigue is considered. The calculations for fatigue life will be performed in OrcaFlex software and taking into account DNV standard for fatigue analysis DNV-RP-C203 (DVN, 2010c).

8.2 Wave Induced Fatigue

8.2.1 Fatigue analysis based on S-N Curve

For the fatigue analysis in this thesis, S-N curve methodology was implemented. The S-N curve is the stress range versus number of cycles to failure. The S-N curves are used to stablish the fatigue damage of the riser in seawater with cathodic protection. Likewise, these curves determine the number of stress cycles to failure (N) for a certain constant stress range (S). The following formula describes the S-N curve (DVN, 2010c):

$$\log \mathrm{N} = \log \bar{\mathrm{a}} - \mathrm{m} * \log \Delta\sigma \qquad \textit{Eq: 8.2.1}$$

Having that;

N Predicted number of stress cycle to failure for stress range $\Delta\sigma$

$\Delta\sigma$ Stress range

log $\bar{a}$ Intercept of Log N-axis by S-N Curve, empirical constant

m Negative inverse slope of S-N Curve

$$\Delta\sigma = \Delta\sigma_o * SCF\left(\frac{t}{t_{ref}}\right)^k \qquad \textit{Eq: 8.2.2}$$

Where;

$\Delta\sigma_o$ Nominal stress range

t_{ref} Reference wall thickness equal 25mm for a welded connection

t Thickness through which a crack will most likely grow. Where t_{ref} is used for thickness less than $t_{ref.}$

k Thickness exponent on fatigue strength

Giving that; 0.10 for tubular butt welds made from one side.

0.25 for threaded bolts subjected to stress variation in the axial direction.

SCF Stress Concentration Factor

Testing data of fatigue for small specimens which were subjected to dynamic loading in test laboratories are consider for the elaboration of the S-N Curve, (DNV, 2010c). Figure 8.1 illustrates S-N Curves for seawater environments with cathodic protection. For fatigue analysis, this study will take into account D-curve (Red color). The demonstration in the use of the S-N curve was made by Karunakaran et al. (2006).

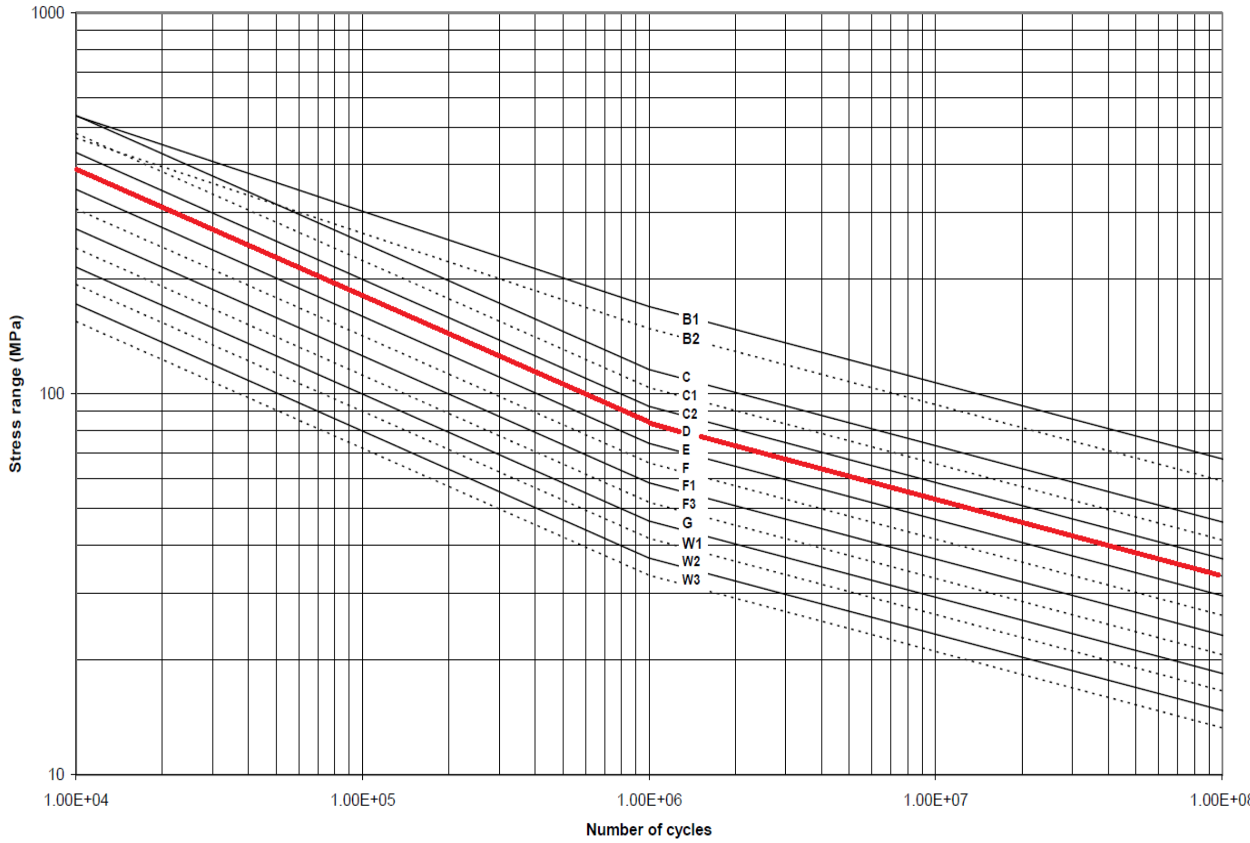


Figure 8. 1. S-N Curves in seawater with cathodic protection (D-Curve in Red) (DVN, 2010c)

The fatigue limit is set a 10^7 cycles considering S-N curve. The cut-off stress range for Curve D is 52.6 Mpa. Similarly, the value selected for the stress concentration factor SCF is 1.2.

The fatigue damage calculation consider 32 sea states, each one with its respective Hs and Tp. Each of the eight directions is weighted with a respective probability of occurrence for Gulf of Mexico. The combination of the directional probabilities for the eight directions in each sea state becomes the total fatigue damage. Table 8.1 shows the condensed Wave Scatter Diagram implemented in this study, the value for the different 32 representative sea states for the evaluation of the fatigue performance of the two risers SCR and RCSCR.

For example for sea state 13, the significant wave height is 6.25m. The peak period is 11.2 and the gamma is 1.8. The 8 directions (N, NE, E, SE, S, SW, W, NW) are weighted with their respective probability of occurrence as shown in Figure 8.2.

Table 8. 1. Wave Scatter Diagram (per thousand) for GoM *

Bin #	Hs (m)	Tp (s)	Total
1	***0,25***	3,4	156,861
2	***0,75***	5,1	443,197
3	***1,25***	6,1	208,594
4	***1,75***	7,0	104,391
5	***2,25***	7,7	47,024
6	***2,75***	8,2	22,004
7	***3,25***	8,8	9,937
8	***3,75***	9,3	3,871
9	***4,25***	9,7	1,806
10	***4,75***	10,1	0,697
11	***5,25***	10,5	0,445
12	***5,75***	10,9	0,285
13	***6,25***	11,2	0,162
14	***6,75***	11,5	0,190
15	***7,25***	11,8	0,168
16	***7,75***	12,1	0,110
17	***8,25***	12,4	0,043
18	***8,75***	12,7	0,036
19	***9,25***	13,0	0,036
20	***9,75***	13,2	0,042
21	***10,25***	13,5	0,024
22	***10,75***	13,7	0,021
23	***11,25***	13,9	0,010
24	***11,75***	14,2	0,009
25	***12,25***	14,4	0,008
26	***12,75***	14,6	0,009
27	***13,25***	14,8	0,006
28	***13,75***	15,0	0,003
29	***14,25***	15,2	0,002
30	***14,75***	15,4	0,002
31	***15,25***	15,6	0,003
32	***15,75***	15,8	0,003
	Total		**1000**

*Full table for each direction and other associated parameters cannot be shown fully as it is property of Subsea7.

Similarly, Figure 8.2 illustrates the subdivision of the sea state scatter diagram with their respective representative blocks, as an illustration that all the possible sea states in the Gulf of Mexico are being considered.

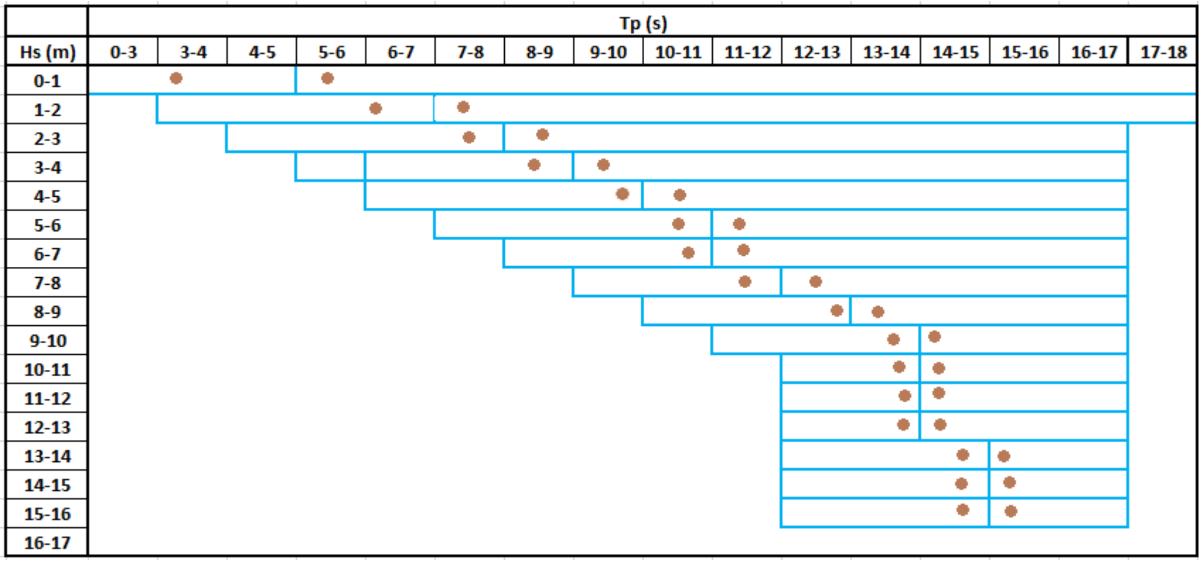


Figure 8. 1 Representation of subdivision of the sea state scatter diagram blocks for Gulf of Mexico. 32 sea states were considered.

By using the 8-wave directions and its respective directional probability, the fatigue damage from the 32 representative sea states is weighted. The directional probabilities are shown in Table 8.2.

Table 8. 2. Wave Direction and probabilities

Wave Direction	Angle (°)	Directional Probability (%)
N	*0*	8,09
NE	*45*	14,12
E	*90*	20,24
SE	*135*	27,28
S	*180*	13,41
SW	*225*	4,52
W	*270*	5,90
NW	*315*	6,45
		100,00

The total accumulated fatigue damage is calculated using the following formula (DVN, 2010c):

$$D_{fat} = \sum_{i=1}^{p} \frac{n_i}{N_i} \qquad \text{Eq: 8.2.3}$$

Where: D_{fat} Accumulated fatigue damage

n_i Number of stress cycles in each block

N_i Number of cycles for failure at constant stress range

p *Number of stress blocks considered*

For the Design Fatigue Factor (DFF), the value considered was 10 according to what was discuss in chapter 3.7 in the fatigue limit state description; the analysis takes into account a high safety class. The expected design life is 25 years and the minimum acceptable fatigue life is 250 years.

A long-term cumulative fatigue damage is considered where simulations of 45 minutes were run for each sea state with a total 256 simulations (32x8). Then, the fatigue damage was estimated checking all the blocks using the rain-flow counting technique and 16 point around the circumference of the riser. The sub-total damage for each of the 32 sea states for each of the 8 direction is then sum up to obtain the total damage. This procedure is implemented with the used of the option for fatigue analysis in OrcaFlex software.

8.2.2 Results for fatigue analysis

Both the conventional SCR and RCSCR were considered for the analysis. The critical locations selected were at 1.5 mts below the Flex Joint, the section of the arc-length of the riser with the implemented residual curvature (only for RCSCR) and the touchdown point. This checking considered the S-N Curve D, where the fatigue life results for the two riser configurations is shown in the Table 8.3. It can be observed that the minimum fatigue life for the SCR occurred at the area of the TDP with a value of 243 years. This value is lower than the acceptable fatigue life of 250 years. SCR does not satisfy the allowable value for the selected SEMI in the Gulf of Mexico.

Table 8. 3: Fatigue Analysis Results for SCR and RCSCR

Location	**SCR**	**RCSCR**
	Years	
1.5 mts Below Flex Joint	3957	3741
Un-Straightened Section (Min. Value)*	11000	599
TDP	243	863

*For SCR does not apply.

On the other hand, according to Table 8.3 and Figure 8.3, the application of the un-straightened section for the RCSCR configuration improve the minimum fatigue life of the riser. The minimum value obtained was 599 years and occurred at the section with residual curvature. For the touchdown area, the fatigue life increased from 243 years to 863 years. The application of residual curvature moves the minimum fatigue life from the TDP to the area where the section with residual curvature is applied.

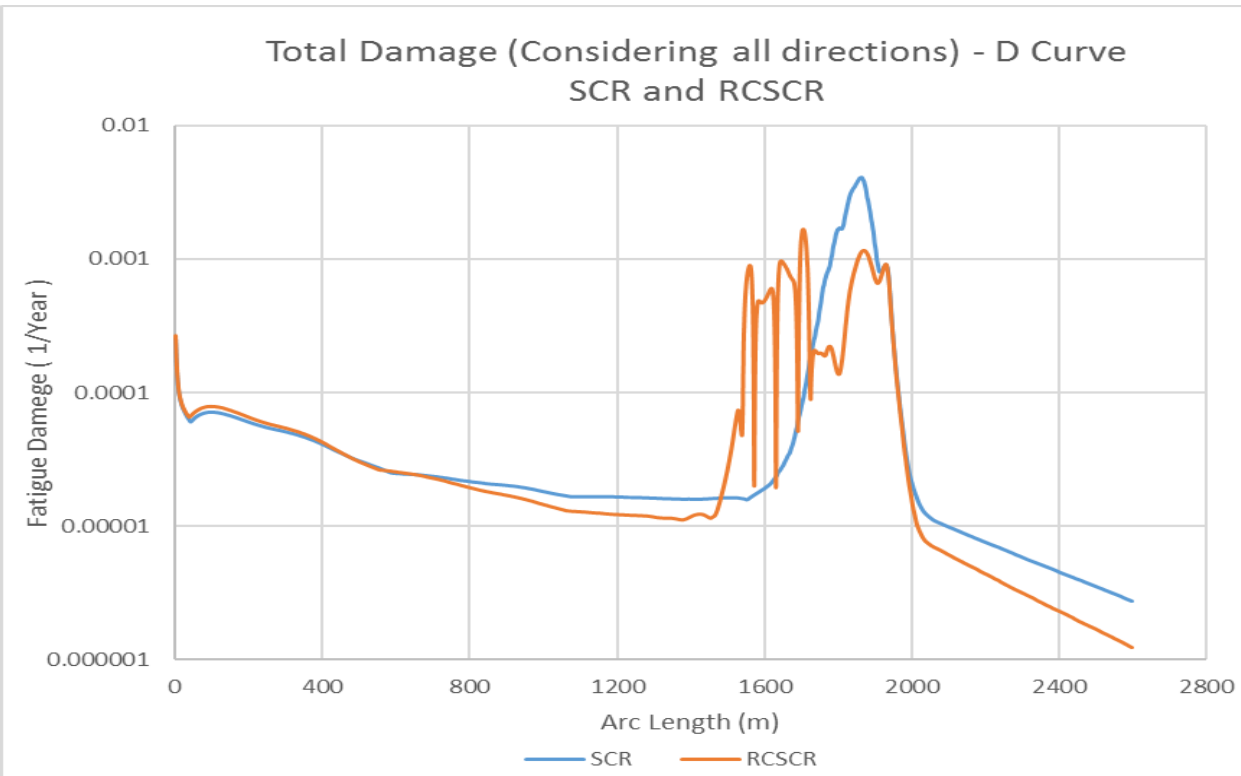


Figure 8. 2: Total Fatigue Damage for SCR and RCSCR

Figure 8.3 illustrates the value for the total fatigue damage through the arc-length in the two riser configurations. The line in blue color depicts the value for the fatigue damage of the SCR, which shows that the minimum fatigue life occurred at the TDP (243 years). RCSCR (Orange line) shows two local peaks, one in the un-straightened section (599 years) and the other in the TDP (863 years). It can be observed that the section move away from the TDP the minimum fatigue life of the riser and improve the values in the area in contact with the seabed, the RCSCR configuration bring lower values for fatigue damage than the SCR.

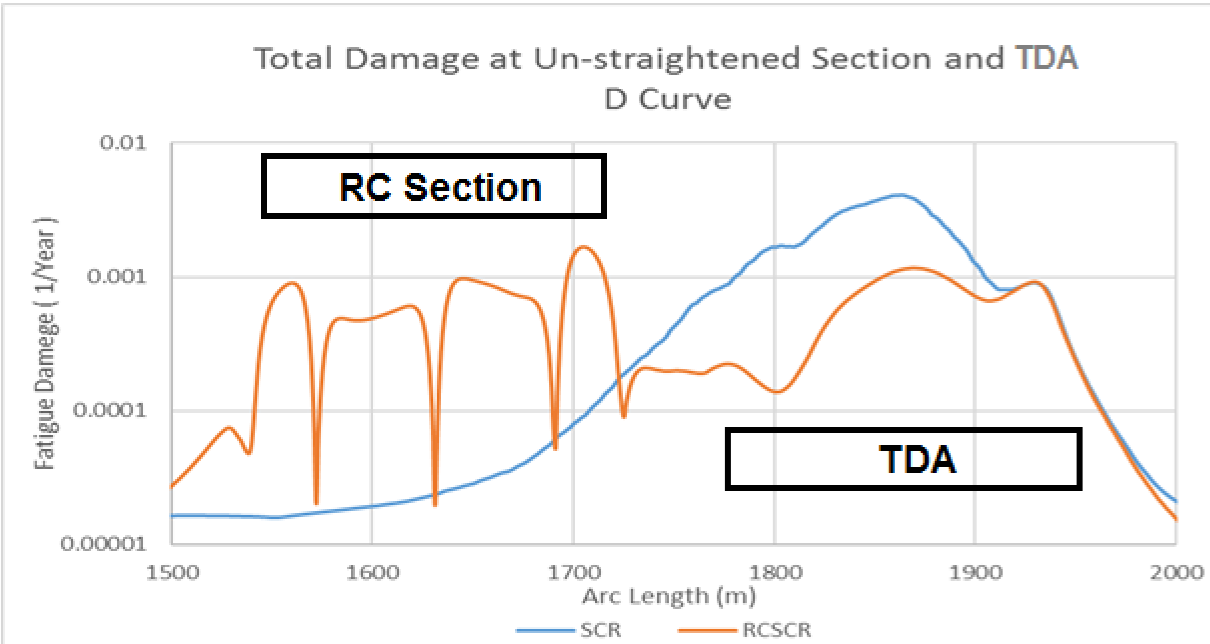


Figure 8. 3: RC and Touchdown Area - Total Fatigue Damage for SCR and RCSCR

Total damage with the use of the D-curve at the un-straightened section and the touchdown area is presented in detail in Figure 8.4. It can be seen how the RC section absorb the fatigue load out from the TDA reducing its value. The Residual Curvature Method is, as happened with the extreme condition analysis, a self-limiting process where its implementation effectively lower the value of the fatigue damage for the riser but the un-straightened section itself becomes the most critical location. RCM reduces fatigue load on a SCR; however, its application have to be carefully implemented. To sum up, RCSCR works for wave induced fatigue in GoM.

Chapter 9. Conclusions and Recommendations

9.1 Conclusions

This thesis describes the feasibility of application of the Residual Curvature Method in free hanging risers, such as Steel Catenary and Weight Distributed Steel Catenary Riser, for the reduction of stress and fatigue loads providing these two types of risers have the capacity to handle higher floater motions. This new configuration is named as RCSCR and RC-WDSCR.

After describing riser design theory, riser installation methods and residual curvature theory in Reel-lay method, models were created with OrcaFlex Software and DNV standards. Static and Dynamic analysis, considering effective tension, bending moment, maximum compression and utilization, were performed for the evaluation of the selected deepwater free hanging steel riser configurations, considering the capacity for coping with large floater motion. It was validated that for SCR and WDSCR, bending moment is the design driver as the risers have structurally greater capacity to withstand axial loads than lateral loads. ULS-Near position and with content (Full internal fluid and pressurize line) was confirmed as being the most critical case.

A Deep Draft Floater was originally used for this study, and it was determined that it performed better than the SEMI selected later. For a 100-year 3h sea state in hurricane conditions (Hs=15.8 m and Tp=16.9 s), the result for the maximum downward velocity at the hang-off point was 2.31 m/s, while with the selected SEMI the result was 4.27 m/s. The capacity of the SCR was determined to be 2.64 m/s. Then, as the SCR can work with the selected DDF, the SEMI ended up being chosen for the proper study of the RC on SCR, as the utilization factor exceeded the allowable value with this type of floater.

The Residual Curvature Method was implemented on a Steel Catenary Riser and a parametric study was performed for the most optimum location and configuration for the application of the un-straightened sections on the Steel Catenary Riser. It was determined that the RCM is a self-limiting process, where the section with residual curvature is able to absorb compressive forces, improve utilization and fatigue in the touch down area TDA; however, the section itself resulted in more bending moment, utilization and fatigue where it was implemented, limiting its application. It is worth mentioning that the more curvature that is applied, more compressive forces are absorbed, although the utilization on the area where the RC section is applied increases. For the RCSCR, the application of residual curvature become relevant influencing the maximum bending moment; the section with RC can become the design driver parameter for the riser when applied.

It was determined that there is a location near the TDP were the section performed optimally. For the conventional SCR configuration studied (39mm wall thickness and 10-inch ID), it was found that a single un-straightened section (which is made up of 4 subsections) of 180m length (12% Water deep), 0.009 m^{-1} of curvature (obtaining a residual strain of 0.15% in the section) and implemented at 35m over the seabed reduces the utilization and maximum compression the most.

Comparison of results for the implementation of Residual Curvature Method on the SCR and WDSCR configurations were made, taking into account DNV-Utilization and the capability to handle with floater motion. This was done by determining the maximum downward velocity at the hang-off point as the main criteria for riser integrity and design for the different riser configurations and evaluating the strength (extreme response study) as well as fatigue performance.

Extreme Response Study

The application of un-straightened sections through the Residual Curvature Method on the SCR and WDSCR have shown to be a feasible way to increase their capacity to withstand higher downward velocities that occurred at the hang-off point, improving their capacity of handling with higher stress. For the conventional SCR, the implementation of RCM has shown to improve the capacity of the riser to cope with a downward velocity at the hang-off point of 2.94 m/s, where initially it was able to handle 2.64 m/s, giving an increase of 11%. Similarly, the RC-WDSCR could handle a downward velocity of 4.01 m/s, where originally, WDSCR configuration could handle 3.2 m/s, obtaining an increase of 25%.

The Residual Curvature Method applied in a SCR helps to reduce stress and perform better with larger floater motion by lowering the value of the utilization factor and reducing compressive forces; however, as mentioned, it is a self-limiting process where if more curvature is applied, the value of the utilization is reduced in the TDA but increases in the RC section.

Even though there was an improvement in the performance in strength of the SCR and WDSCR; the maximum downward velocity at the hang-off point (4.27 m/s) for the selected SEMI under the 100-year sea state in hurricane conditions could not be handle by implementing this technique in this study.

Fatigue Analysis

Wave induced fatigue analysis was performed on the two riser configurations, SCR and RCSCR. In total 256 load cases from 8 wave directions where applied using a wave scatter diagram from Gulf of Mexico considering irregular sea states with JONSWAP spectra. The results for the conventional SCR have shown to be not enough for the acceptance criteria of 250 years, giving 243 years for the TDP.

On the other hand, after applying residual curvature for the RCSCR configuration, a reduction in fatigue damage was observed; for instance, the minimum fatigue life for the riser improved to 599 years. This minimum fatigue life for RCSCR was obtained at the un-straightened section. Additionally, the minimum fatigue life at the TDP increased from 243 years in the SCR to 863 years.

The Residual Curvature Method successfully reduced fatigue loads on the SCR and removed the maximum fatigue damage from the TDA to the location of the section with residual curvature. RCM is a self-limiting process where its implementation effectively lower the value of the fatigue damage for the riser but the un-straightened section itself becomes the most critical location. These observations were made considering D-Curve.

9.2 Recommendations

The following studies and investigations can be performed on free hanging riser systems with the implementation of the Residual Curvature Method.

- Create a fully automatized algorithm in Python applied in OrcaFlex, to execute a more exhaustive parametric study to fully optimize the application of the RCM in the SCR, for the hanging section, in order to understand more deeply the reduction of stress and fatigue loads.

- The values for the downward velocities at the hang-off point to which the RCSCR and RC-WDSCR can handle (2.94 m/s and 4.01m/s), need to be properly validated with the implementation of an optimized parametric study in Python and more Load Cases.

- Analyze the riser-soil interaction when applying residual curvature in sections in contact with seabed.

- Study the application of the RC sections in locations along the riser that lay over the seabed, adjusting the riser to the topography. In other words, study the installation of risers shaping it to the seabed topography; obtaining or improving the active resistance.

- Study the influence of the section with residual curvature and internal flow.

- Analyze how the residual curvature can eliminate straightening trials for reel-laid in SCR.

- Study stability issues regarding the application of sections with residual curvature in the riser checking rotation.

- Check the effect of the application of section with residual curvature to Vortex Induced Vibration of the riser.

- Implementation of RCM on Steel Lazy Wave Riser configuration to reduce the number of buoyancy modules. RC-SLWSCR.

- Analyze how the curvature in the un-straightened section reduces or increase its value throughout the life of the riser while in operation.

References

All seas group. (2015). Audacia pipelay vessel. Retrieved 03 17, 2019, from https://allseas.com/equipment/audacia/

API RP 2RD. (2006). *Dynamic Risers for Floating Production Systems.* Houston.

Baarholm, R., & Karunakaran, D. (2013). COBRA: An Uncoupled Riser System for Ultra-deep Water in Harsh Environment. *OTC-23945.* Offshore Technology Conference.

Bai, Y., & Bai , Q. (2012). *Subsea Engineering Handbook.* Oxford, UK: Elsevier.

Baynum, D., & Havik, K. (1981). Marine Pipeline Roll Parameters study. *Oil and gas Journal*, 138-146.

BBSE Bureau of Safety and Environmental Enforcement for Offshore Structures. (2018). *Deepwater Development Systems*. Retrieved 02 27, 2019, from https://www.bsee.gov/site-page/deepwater-development-systems-in-the-gulf-of-mexico-basic-options

Burgess, M., & Lim, F. (2006). Installation of Deepwater Risers. *2H Offshore*.

Carter, B., & Ronald, B. (1998). Deepwater Riser Technology. *Society of Petroleum Engineers*.

Costal Marine Institute. (2008). *Deepwater Currents in the Easter Gulf of Mexico.* Baton Rouge.

DNV . (2010a). *DNV-OS-F201: Dynamic Risers.* Oslo.

DNV . (2010b). *DNV-OSS-302 Offshore Riser Systems.* Oslo.

DNV. (2007). *DNV-OS-F101: Submarine Pipeline Systems.* Oslo.

DNV GL. (2015). *Position Mooring DVNGL-OS-E301.* Oslo.

DVN. (2010c). *DNV-RP-C2013: Fatigue Design of Offshore Steel Structures.* Norway.

Endal , G., Nystrøm, P., & Lyngsaunet, O. (2015). Lay Method to make Pipelines Conform to Uneven seabed topography. *International Society of Offshore and Polar Engineers. ISOPE*.

Endal, G. (2005, Jun 28). *USA Patent No. US 6,910,380 B2: Method for Pipelaying from a Coil to the Sea Bed, Controlling Thermal Expansion.*

Endal, G., & Nystrøm, P. (2015). Benefits of Generating Pipeline Local Residual Curvature During Reel- and S-lay Installation. *OPT*.

Endal, G., & Nystrøm, P. (2015). Benefits of Generating Pipeline Local Residual Curvatures during Reel- and S-lay Installation.

Endal, G., Giske, S., Moen, K., & Sande, S. (2014). *Reel-lay Method to Control Global Pipeline Bucking Under Operating Loads.* Norway: OPT.

Endal, G., Giske, S., Moen, K., & Sande, S. (2014). Reel-Lay Method to Control Global Pipeline Buckling Under Operating Loads. *International Conference on Offshore Mechanics and Artic Engineering.* San Francisco, California, USA: OMAE.

Endal, G., Ness, O., Verley, R., Holthe, K., & Remseth, S. (1995). Behavior of Offshore Pipelines Subjected to Residual Curvature During Laying. *OMAE, Pipeline Technology, 5*.

Endal, G., Nystrøm, P., & Lyngsaunet, O. (2015). Lay Method to make Pipelines Conform to Uneven seabed topography. *International Society of Offshore and Polar Engineers. ISOPE*.

Equinor. (2013, March 18). Skuld has started production. Norway. Retrieved 04 05, 2019, from https://www.equinor.com/en/news/archive/2013/03/18/18MarSkuld.html

Gate Energy. (2015). *Introduction to Risers*. Retrieved 04 26, 2019, from https://www.gateinc.com/gatekeeper/gat2004-gkp-2015-02

Gemilang, G. (2015). *Feasibility Study of Selected Riser Concept in Deep Water and Harsh Environment [Master Thesis].* Stavanger: University of Stavanger.

Gudmestad, O. (2015). *Marine Technology and Operations.* Southampton, UK: WIT Press.

Hoffman, J., Yun, H., & Modi, A. (2010). Parque das Conchas (BC-10) Pipeline, Flowline and Riser System Design, Installation and Challenges. *Offshore Technology Conference*.

Hu, X., Duan, M., & Lui, P. (2012). Risk and Reliability Analysis of Deepwater Reel-Lay Installation: A Scenario Study of Pipeline during the Process of Tensioning. *Natural Resources*, 8.

International Energy Agency IEA. (2018). *Total Primary Energy Supply TPES.* Paris.

Karamanos, S., Varelis, G., & Chatzopoulou, G. (2016). Finite element analysis of cyclically-loaded steel pipes during deep water reeling installation. *Ocean Engineering, 124*, 113-124.

Karunakaran, D. (2014). Lecture Slices, course of Risers and Pipelines. Stavanger: University of Stavanger.

Karunakaran, D. (2017). Pipeline and Risers Lecture Notes, University of Stavanger. Stavanger, Norway.

Karunakaran, D., & Baarholm, R. (2013). Cobra Riser Concept for Ultra-Deepwater Condition. *Offshore Technology Conference*.

Karunakaran, D., & Jones, R. (2013). Fatigue Enhancement of SCRs: Design Applying Weight Distribution and Optimized Fabrication. *Offshore Technology Conference. OTC 23945*.

Karunakaran, D., & Jones, R. (2014). Weight Distributed SCR's with Quality Fabrication from Large Motion. *Offshore Technology Conference.* Kuala Lumpur.

Karunakaran, D., & Jones, R. (2014). Weight Distributed SCRs with Quality Fabrication from Large Motion Floaters. *Offshore Technology Conference*.

Karunakaran, D., Frønsdal, M., & Baarholm, R. (2016). Steel Lazy Wave Riser with Tether for FPSO with Disconectable Turret for Iceberg Conditions. *Offshore Technology Conference*.

Karunakaran, D., Meling, T., Kristoffersen, S., & Lund, K. (2005). Weight Optimized SCRs for Deepwater Harsh Environments. *Offshore Technology Conference*.

Karunakaran, D., Nordsve, N., & Olufsen, A. (1996). An Efficient Metal Riser Configuration for Ship and Semi Based Production System. *International Offshore and Polar Engineering Conference* (pp. 156-162). Los Angeles, USA: The international Society of Offshore and Polar Engineers.

Karunakaran, D., Seguin, B., & Legras, J. (2015). Riser Solution for turret-Morred FPSOs With or Without Disconnectable Turret. *Offshore Technology Conference. OTC-25651-MS*.

Katla, E., Mork , K., & Hansen, V. (2001). Dynamic Risers: Introduction and Background to the New DNV Offshore Standard (OS-F201). *Offshore Technology Conference*.

Kavanagh, W., Lou, J., & Hays, P. (2003). Design od Steel Risers in Ultra Deep Water - The Influence of Recent Code Requirements on wall Thickness Design for 10000 ft Water Depth. *Offshore Technology Conference*.

Kyriakides, S., & Corona, E. (2007). Mechanics of Offshore Pipelines.

Luppi, A., Cousin, G., & O'sullivan, R. (2014). Deep water Hybrid Riser System . *Offshore Technology Conference*.

Nystrøm, P., Endal , G., & Lyngsauner, O. (2015). Lay Method to Allow for Direct Tie-in of Pipelines. *International Ocean and Polar Engineering Conference, ISOPE*, 164-174.

Oilfield Wiki. (2019). *Subsea Production Riser*. Retrieved 04 02, 2019, from http://oilfieldwiki.com/wiki/Subsea_Production_Riser

Orcina. (2016). OrcaFlex Manual 10.1a. Available at https://www.orcina.com/index.php. Dalton Gate, Cumbria, LA12 7AJ, UK. Retrieved 03 2019, from https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/index.php

Palmer, A., & King, R. (2004). *Subsea Pipeline Engineering.* Tulsa, Oklahoma: PennWell Corporation.

Phifer, E., Kopp, F., & Swanson, R. (1994). Design and Installation of Auger Steel Catenary Risers. *Offshore Technology Conference. OTC7620*.

Ramiro, A. (2018). *Thesis: Estudo da Curvatura Residual Aplicada ao Problema da Compressão Dinâmica em Risers Rígidos em Catenária Livre.* Rio de Janeiro: Universidade Federal do Rio de Janeiro.

Roy, A., Rao, V., Charnaux, C., Ragupathy, P., & Sriskandarajah, T. (2014). Straightener Settings For Under-Straight Residual Curvature of Reel Laid Pipe.

Rystad Energy Research Analysis. (2018). *All-Time low for discovery resources in 2017.* Oslo.

Saipem. (2010). Semi-submersible crane and pipelaying (J-lay) DP vessel. Saipen 7000. Milan, Italy. Retrieved 04 05, 2019, from http://www.saipem.com/SAIPEM_en_IT/scheda/Vessels/Saipem+7000.page

Subsea7. (2015). Reel lay Vessel " Seven Oceans". Retrieved from https://www.subsea7.com/content/dam/subsea7/documents/whatwedo/fleet/rigidpipelay/Seven%20Oceans.pdf

Subsea7. (2015). *Riser Technology Catalog.* Sutton, UK.

Tewolde, A. (2017). *Pipelay With Residual Curvature.* Stavanger: University of Stavanger [Thesis].

TReK STS. (2016). *Decoking Flexible Pipes*. Retrieved 04 21, 2019, from http://www.trektank.com/index.php/decoking-flexible-pipes

University of Cambridge. (2004). Bending and torsion of beams. Retrieved 03 18, 2019, from https://www.doitpoms.ac.uk/tlplib/beam_bending/pole_vaulting.php

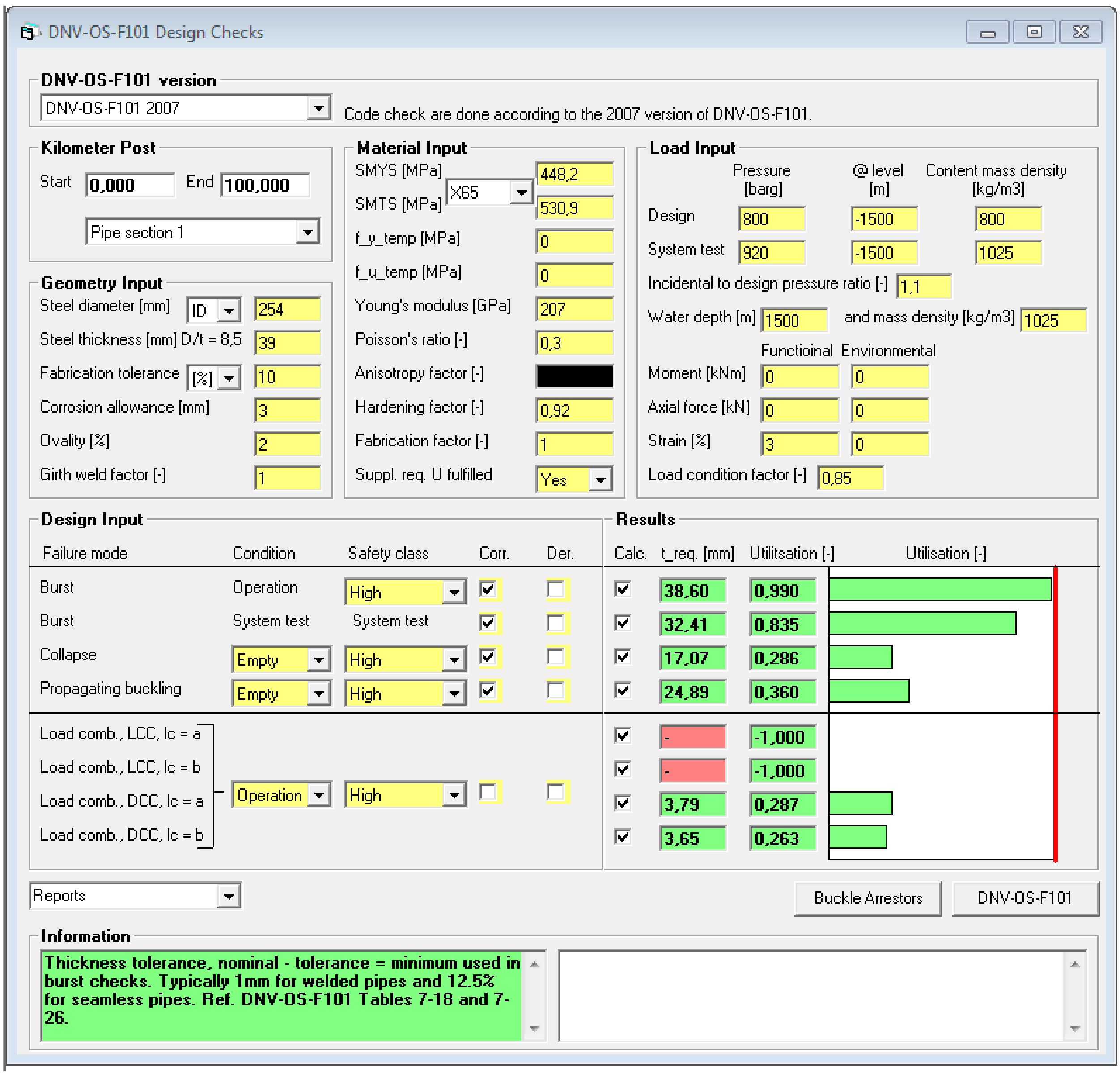
Vaughan, N., Foss, P., Rødstøl, A., & Nystrøm, P. (2018). Prediction of Pipeline Rotation During the Installation of Residual Curvature Section by Reel-Lay. *International Ocean and Polar Engineering Conference, ISOPE*, 151-164.

Wartsila Encyclopedia of Marine Technology. (2016). Pipelaying Methods. Retrieved 04 05, 2019, from https://www.wartsila.com/encyclopedia/term/pipelaying-methods

Appendices

Appendix A. Pipeline Engineering Tool and Wall Thickness Calculation

Screenshot of the interface of software PET (Pipeline Engineering Tool) used for the calculation of Steel Catenary Riser wall thickness. Water depth of 1500 m is considered in the input for the calculation.



Appendix B. OrcaFlex Description

This numerical tool is used for dynamic analysis of offshore structures, According to Orcina, 2016; "it is fully 3D non-linear domain finite element program, it is able to calculate and handle large deflections of a flexible structure (slender structure)", it is used to achieve modal analysis on the whole system or individual lines. The software considers, among others, the following guidelines for design and analysis of offshore systems: (Gudmestad, 2015)

- API-RP-1111 Standard, which is used as a guideline for construction, design, and maintenance as well as operation of subsea pipelines implementing Limit State Design.
- DNV-OS-F101. Submarine Pipeline Systems
- DNV-OS-F201. Offshore standards for dynamic risers
- PD-80010.

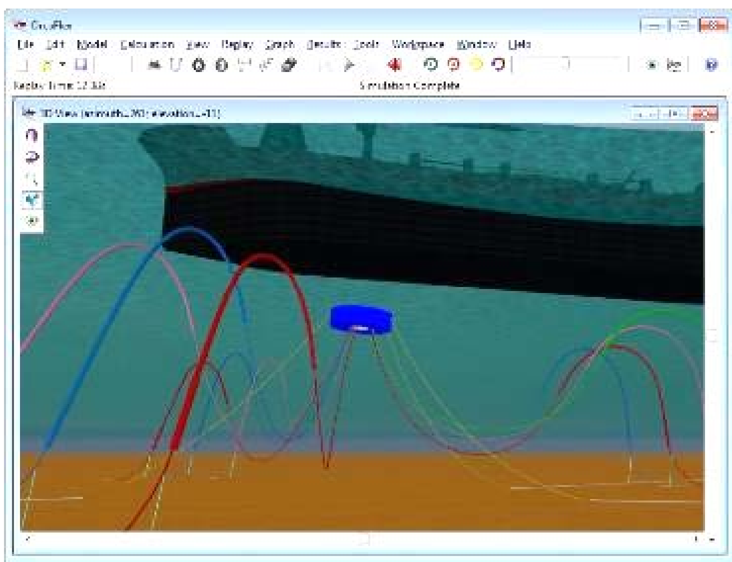


Figure B1. OrcaFlex Screenshot. An OrcaFlex model of an FPSO. system with a releasable turret. (Orcina, 2016)

Some areas of application include (Orcina, 2016):

- Risers systems: Steel Catenary Risers (SCRs), Tensioned marine risers, Hybrid Riser systems, Flexible risers and umbilicals.

- Mooring lines: Jetty mooring systems, Turret (external and internal) moored systems, Spread mooring systems, Oceanographic mooring systems, Single Point Moorings among others.
- Installation Analysis: Cable lay dynamics, Riser installation, Through-splash zone deployment, Pipelay analysis, Anchor and mooring deployment, Deep water installation of subsea hardware among other applications. (Orcina, 2016)

B.1 Overview of the software.

OrcaFlex is a user-friendly software tool that possess excellent characteristics as well as graphic representation of models.

According to Tewolde, 2015; "A 3-D view is showing the marine environment to the user when the program starts; the view displays the sea surface, the seabed, and a dark empty space representing the surrounding environment". The main window is shown in Figure B2. Where the brown line depicts the bottom of the sea, and the blue line depicts the sea surface. (Gudmestad, 2015) and (Tewolde, 2017).

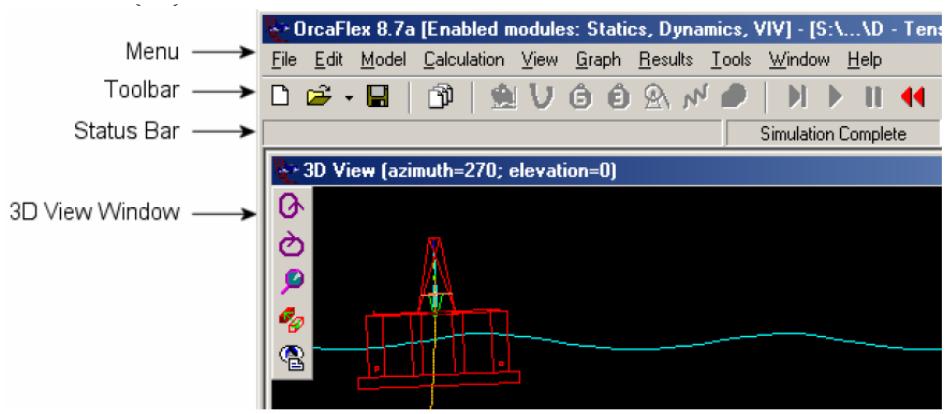


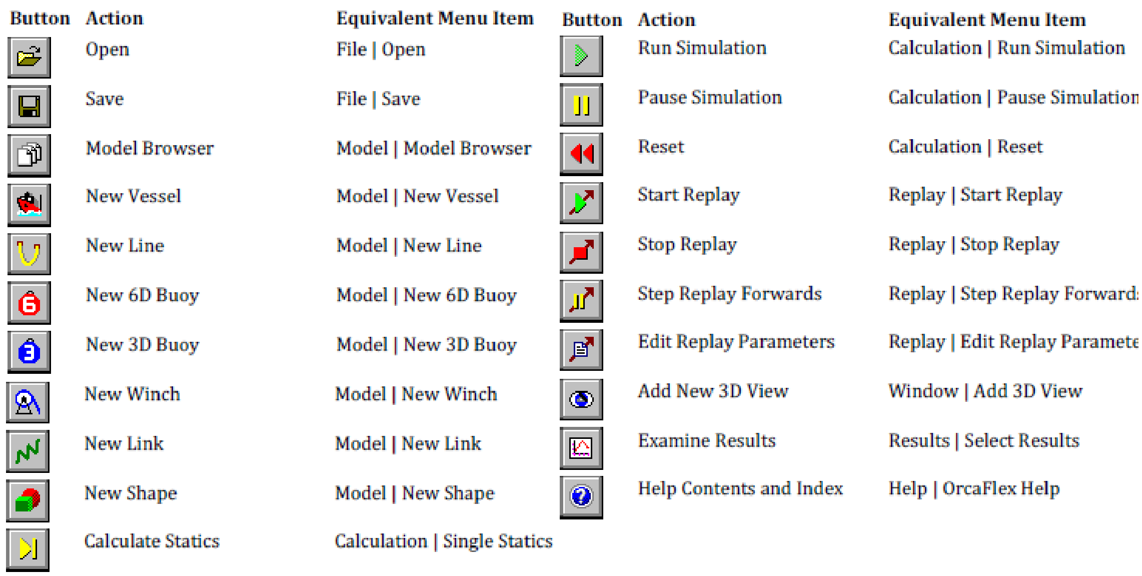
Figure B2. Screenshot of the main window – OrcaFlex. (Orcina, 2016)

Menu bar: The menu bar has many commands including commands for opening, saving, printing and exporting. The menu bar has data and object editing facilities.

Toolbar: It is the shortcut to the menu bar; this bar present a shortcut to access the majority of the commands.

Status bar: The status bar offers information about how current action is progressing, and is divided between the state indicator, information box and message box.

3D view: The 3D view window displays the current model in a graphic form and provides representation of each part of a system.



<table>
<tr><th>Button</th><th>Action</th><th>Equivalent Menu Item</th><th>Button</th><th>Action</th><th>Equivalent Menu Item</th></tr>
<tr><td></td><td>Open</td><td>File | Open</td><td></td><td>Run Simulation</td><td>Calculation | Run Simulation</td></tr>
<tr><td></td><td>Save</td><td>File | Save</td><td></td><td>Pause Simulation</td><td>Calculation | Pause Simulation</td></tr>
<tr><td></td><td>Model Browser</td><td>Model | Model Browser</td><td></td><td>Reset</td><td>Calculation | Reset</td></tr>
<tr><td></td><td>New Vessel</td><td>Model | New Vessel</td><td></td><td>Start Replay</td><td>Replay | Start Replay</td></tr>
<tr><td></td><td>New Line</td><td>Model | New Line</td><td></td><td>Stop Replay</td><td>Replay | Stop Replay</td></tr>
<tr><td></td><td>New 6D Buoy</td><td>Model | New 6D Buoy</td><td></td><td>Step Replay Forwards</td><td>Replay | Step Replay Forward</td></tr>
<tr><td></td><td>New 3D Buoy</td><td>Model | New 3D Buoy</td><td></td><td>Edit Replay Parameters</td><td>Replay | Edit Replay Paramete</td></tr>
<tr><td></td><td>New Winch</td><td>Model | New Winch</td><td></td><td>Add New 3D View</td><td>Window | Add 3D View</td></tr>
<tr><td></td><td>New Link</td><td>Model | New Link</td><td></td><td>Examine Results</td><td>Results | Select Results</td></tr>
<tr><td></td><td>New Shape</td><td>Model | New Shape</td><td></td><td>Help Contents and Index</td><td>Help | OrcaFlex Help</td></tr>
<tr><td></td><td>Calculate Statics</td><td>Calculation | Single Statics</td><td></td><td></td><td></td></tr>
</table>

Figure B2. OrcaFlex Toolbar. (Orcina, 2016)

B.2 Modeling and analysis

OrcaFlex construct and analyzes a mathematical model of the system being analyzes, the model being build up from a series of interconnected objects, like, Lines, Vessels and Buoys. This software works on the model by moving through a sequence of states, the current sate being shown on the status bar. The following diagram (Figure B4) illustrates the sequence of states used and the actions, results etc. Available for each state. (Orcina, 2016)

In Figure B4, it can be seen he sequence of analysis in OrcaFlex. Figure B5, shows thee coordinate systems uses in OrcaFlex, this includes of a general global coordinate system.

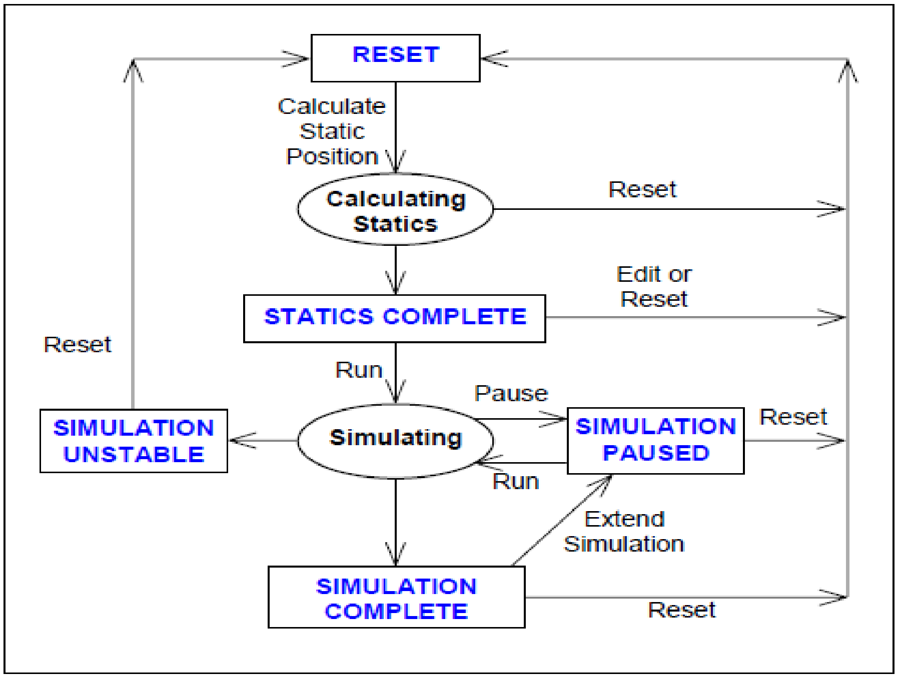


Figure B4. OrcaFlex: Model States. (Gudmestad, 2015)

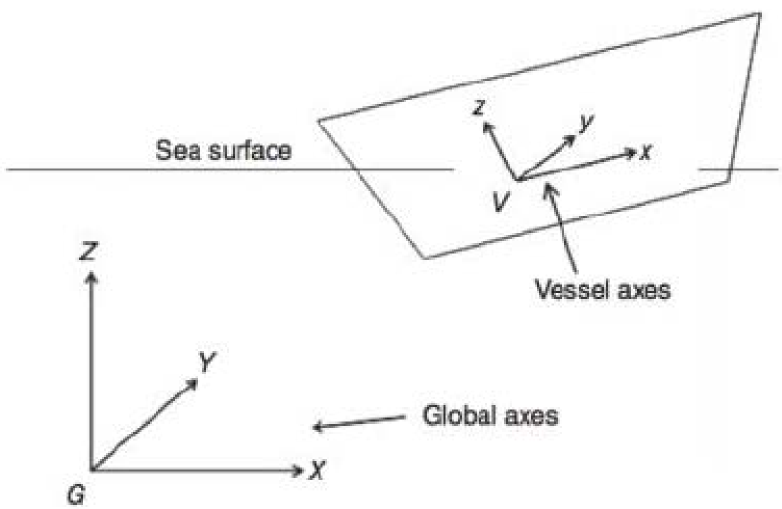


Figure B5. Global and vessel coordinate systems. (Gudmestad, 2015)

Figure B6 shows how the simulation time is specified and how this can be divided into several stages.

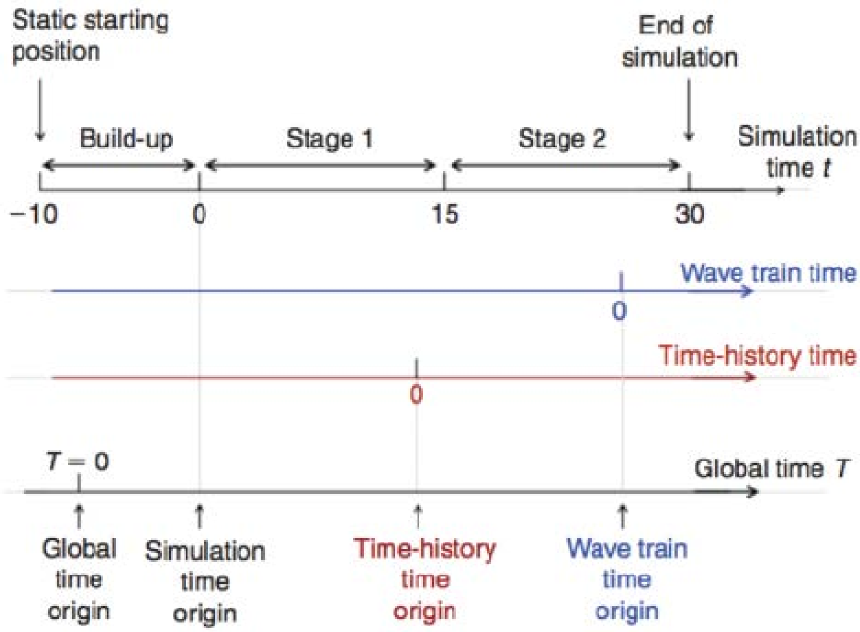


Figure B6. Stages setting in the simulation time and stage. (Gudmestad, 2015)

Appendix C. Application of residual curvature in pipeline using OrcaFlex.

Torsion in lines:

For the application of residual curvature, first it is necessary to enable torsion to the line. Is it possible to enable/disable torsion on a line-by-line basis. That means it is made active/inactive for an individual line. Thus, it is done on a line's data form, not the *line type* data form. Therefore, if open the data form for the 'pipe' in the model, look at the options along the top edge of the form. One of them is entitled *include torsion*. Change that to *yes*. In addition, if it is necessary to modify the settings for *end connection stiffness*, also on the line's data form.

Due to that torsion is enabled, then the stiffness at a line's ends to resist twisting is now active. Because the line's ends are connected rigidly with respect to bending, then the same setting must be used for the twisting stiffness too, *viz.infinity*. Then, type simply the letters 'inf' then press <enter> and OrcaFlex will complete the cell.

Pre-bend Option:

The curvature is applied about the local, nodal x or/and y axes. The simplest is for a bend in one plane only. For example, if the curvature is specified as about the nodal x axes, then the bend will appear to be in the nodal y-z plane.

It is necessary to specify that a section has several segments in order to make the pre-bent sections visible on screen. If you do not have enough segments then a range graph of curvature for the line will show (quite clearly) sudden changes of slope in it, instead of a smooth curve. Because the curvature is specified as radians-per-meter along a section of line, then the value specified gets distributed evenly over all nodes in that section. As a user works along a bent section meter-by-meter, from the start of the section to its end, the total bend accumulates. Hence, at the beginning of the section, the angle of bend from the starting direction is 0°. At the end of that section, the total angle of bend which a user wants should be achieved.

The Figure C1 show an example of bends (90° elbows) in one plane:

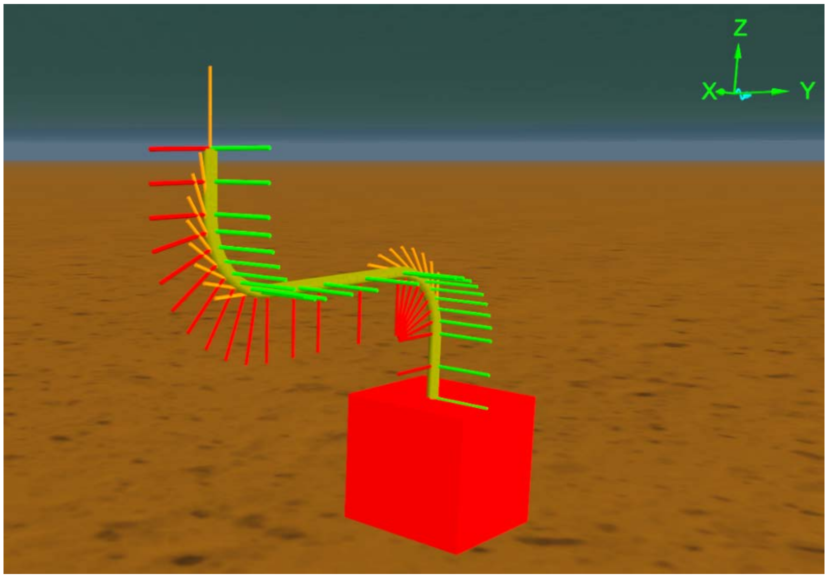


Figure C1: 2D-S-bend single line.

Is it possible to see that the line has 6 sections (Figure D2), the second and fifth of which have pre-bend defined. If make the local, nodal axes visible, it will be shown that the (red) nodal x-axes are in the vertical plane because of the end fitting's orientation at end A. The green y-axes are pointing horizontally. To get the bend in a vertical plane, the pre-bend must be applied about the orthogonal axis direction, in this case the nodal y-axes. The pipe bends one way, then the opposite way, which is why one bend is positive, the other is negative.

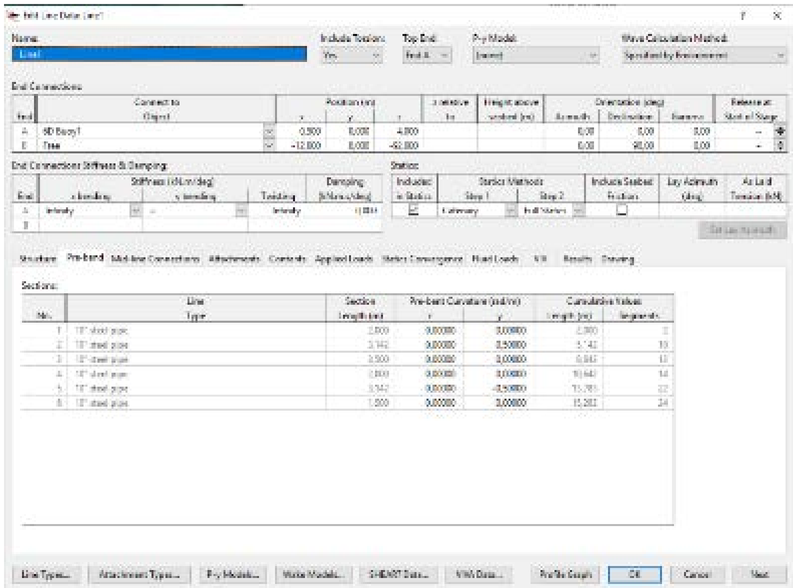


Figure C2: Application of pre-bent option.

Appendix D. Result for Dynamic Analysis SCR and RCSCR

D1. Result for Dynamic Response on SCR

- SCR arc-length= 2796.3 m
- Top angle: 15° in mean position.
- Max. DV: Maximum Downward Velocity at Hang-off point. LC: Load Case
- ULS-Near Most Critical Case

- SCR Strength Response Summary LC=1, Max. DV=1.18 m/s

Load case 1 Full	**Intact ULS**	
	Near	**Far**
Max. Effective top Tension (kN)	4549	5531
Max. Compression (kN)	0	0
Max. Bending Moment (kN.m)	277	117
Max. DNV LRFD Utilization	0,46	0,42

SCR Strength Response Summary LC=2, Max. DV=1.81 m/s

Load case 2 Full	**Intact ULS**	
	Near	**Far**
Max. Effective top Tension (kN)	4940	6167
Max. Compression (kN)	0	0
Max. Bending Moment (kN.m)	486	170
Max. DNV LRFD Utilization	0,65	0,48

SCR Strength Response Summary LC=3, Max. DV=2.35 m/s

Load case 3 Full	**Intact ULS**	
	Near	**Far**
Max. Effective top Tension (kN)	5185	6456
Max. Compression (kN)	0	0
Max. Bending Moment (kN.m)	644	201
Max. DNV LRFD Utilization	0,8	0,51

SCR Strength Response Summary LC=4, Max. DV=2.64 m/s

Load case 4 Full	Intact ULS	
	Near	Far
Max. Effective top Tension (kN)	5353	6756
Max. Compression (kN)	170	0
Max. Bending Moment (kN.m)	834	258
Max. DNV LRFD Utilization	0.98	0.54

SCR Strength Response Summary LC=5, DV=2.94 m/s

Load case 5 Full	Intact ULS	
	Near	Far
Max. Effective top Tension (kN)	5531	7075
Max. Compression (kN)	369	0
Max. Bending Moment (kN.m)	1077	349
Max. DNV LRFD Utilization	1,21	0,57

SCR Strength Response Summary LC=6, Max. DV=3.31 m/s

Load case 6 Full	Intact ULS	
	Near	Far
Max. Effective top Tension (kN)	5759	7279
Max. Compression (kN)	774	110
Max. Bending Moment (kN.m)	1661	600
Max. DNV LRFD Utilization	1,77	0,78

SCR Strength Response Summary LC=7, DV=4.27 m/s

Load case 7 Full	Intact ULS	
	Near	Far
Max. Effective top Tension (kN)	7403	9210
Max. Compression (kN)	1363	1699
Max. Bending Moment (kN.m)	2811	1192
Max. DNV LRFD Utilization	2,86	2,11

D2. Result for Dynamic Response on RCSCR.

- Same riser arc length as used for the SCR= 2796.3 m
- Top angle: 16,8° in mean position (Table 7.19 shows negligible difference in value for maximum utilization at Hang-off point and along the riser as a top angle of value 15°)
- Length of curvature L= 180 m, (30m, 60m, 60m, 30)
- Curvature: 0,009 m^{-1}, Radius of Curvature: 111m
- Single section with residual curvature,
- Applied to 35m over the seabed in mean position (SCR arc length as reference).
- ULS-Near Most Critical Case

RCSCR Strength Response ULS, LC=1, DV=1.18 m/s

Load case 1 Full	**Intact ULS**	
	Near	**Far**
Max. Effective top Tension (kN)	4549	5531
Max. Compression (kN)	0	0
Max. Bending Moment (kN.m)	863	789
Max. DNV LRFD Utilization	0,92	0,89

RCSCR Strength Response ULS, LC=2, DV=1.81 m/s

Load case 2 Full	**Intact ULS**	
	Near	**Far**
Max. Effective top Tension (kN)	4948	6182
Max. Compression (kN)	0	0
Max. Bending Moment (kN.m)	883	792
Max. DNV LRFD Utilization	0,95	0,92

RCSCR Strength Response ULS, LC=3, DV=2.35 m/s

Load case 3 Full	**Intact ULS**	
	Near	**Far**
Max. Effective top Tension (kN)	5256	6454
Max. Compression (kN)	0	0
Max. Bending Moment (kN.m)	896	793
Max. DNV LRFD Utilization	0,96	0,93

RCSCR Strength Response ULS, LC=4, DV=2.64 m/s

Load case 4 Full	**Intact ULS**	
	Near	**Far**
Max. Effective top Tension (kN)	5527	6755
Max. Compression (kN)	30	0
Max. Bending Moment (kN.m)	899	794
Max. DNV LRFD Utilization	0,96	0,95

RCSCR Strength Response ULS, LC=5, DV=2.94m/s

Load case 5, DV=2.94 m/s Full	**Intact ULS**	
	Near	**Far**
Max. Effective top Tension (kN)	5814	7074
Max. Compression (kN)	125	0
Max. Bending Moment (kN.m)	899	795
Max. DNV LRFD Utilization	0,97	0,97

RCSCR Strength Response ULS, LC=6, DV=3.31m/s

Load case 6, DV=3.31 m/s Full	**Intact ULS**	
	Near	**Far**
Max. Effective top Tension (kN)	6262	6989
Max. Compression (kN)	255	0
Max. Bending Moment (kN.m)	986	803
Max. DNV LRFD Utilization	1,13	0,97

RCSCR Strength Response ULS, LC=7, DV=4.27m/s

Load case 7, DV=4.27 m/s Full	**Intact ULS**	
	Near	**Far**
Max. Effective top Tension (kN)	7588	9821
Max. Compression (kN)	387	577
Max. Bending Moment (kN.m)	1249	876
Max. DNV LRFD Utilization	1,35	1,06