KAUNAS UNIVERSITY OF TECHNOLOGY

FACULTY OF MECHANICAL ENGINEERING AND DESIGN

Balajee Govindaraj

MODELLING AND ANALYSIS OF INTERLOCK AND CORRUGATED TUBES FOR ADAPTATION IN A FLEXIBLE OIL PIPELINE

Final project for Master degree

Supervisor
Assoc. Prof. Dr. Marija Eidukeviciute

KAUNAS, 2015

KAUNAS UNIVERSITY OF TECHNOLOGY
FACULTY OF MECHANICAL ENGINEERING AND DESIGN

MODELLING AND ANALYSIS OF INTERLOCK AND CORRUGATED TUBES FOR ADAPTATION IN A FLEXIBLE OIL PIPELINE

Final project for Master degree

Department of Production Engineering

Supervisor
(signature) Assoc. Prof. Dr. Marija Eidukeviciute
(11.06.2015)
Reviewer
(signature) Assoc. Prof. Dr. Kazimieras Juzėnas
(11.06.2015)

Project made by
(signature) Balajee Govindaraj
(date) 11.06.2015

KAUNAS, 2015

KAUNAS UNIVERSITY OF TECHNOLOGY

FACULTY OF MECHANICAL ENGINEERING AND DESIGN

(Faculty)

Balajee Govindaraj

(Student's name, surname)

Department of Production Engineering

(Title and code of study programme)

"MODELLING AND ANALYSIS OF INTERLOCK AND CORRUGATED TUBES FOR ADAPTATION IN A FLEXIBLE OIL PIPELINE"

Final project

DECLARATION OF ACADEMIC HONESTY

11 June 2015

Kaunas

I confirm that a final project by me, **Balajee Govindaraj**, on the subject "**MODELLING AND ANALYSIS OF INTERLOCK AND CORRUGATED TUBES FOR ADAPTATION IN A FLEXIBLE OIL PIPELINE**" is written completely by myself; all provided data and research results are correct and obtained honestly. None of the parts of this thesis have been plagiarized from any printed or Internet sources, all direct and indirect quotations from other resources are indicated in literature references. No monetary amounts not provided for by law have been paid to anyone for this thesis.

I understand that in case of a resurfaced fact of dishonesty penalties will be applied to me according to the procedure effective at Kaunas University of Technology.

(name and surname filled in by hand) *(signature)*

KAUNAS UN IVERSITY OF TECHNOLOGY

FACULTY OF MECHANICAL ENGINEERING AND DESIGN

Approved:	
Head of Production engineering Department	______________________________ *(Signature, date)*
	______________________________ *(Name, Surname)*

MASTER STUDIES FINAL PROJECT TASK ASSIGNMENT
Study programme INDUSTRIAL ENGINEERING AND MANAGEMENT

The final project of Master studies to gain the master qualification degree, is research or applied type project, for completion and defence of which 30 credits are assigned. The final project of the student must demonstrate the deepened and enlarged knowledge acquired in the main studies, also gained skills to formulate and solve an actual problem having limited and (or) contradictory information, independently conduct scientific or applied analysis and properly interpret data. By completing and defending the final project Master studies student must demonstrate the creativity, ability to apply fundamental knowledge, understanding of social and commercial environment, Legal Acts and financial possibilities, show the information search skills, ability to carry out the qualified analysis, use numerical methods, applied software, common information technologies and correct language, ability to formulate proper conclusions.

1. Title of the Project

Modelling and analysis of interlock and corrugated tubes for adaptation in a flexible oil pipeline

Approved by the Dean 2015 May 11 Order No. **ST17-F-11-2**

2. Aim of the project

To model, analyse and compare the characteristics of interlock and corrugated tubes. The results will be used to formulate the recommendations for interlock tube structure as a part of flexible offshore oil pipelines.

3. Structure of the project

- To establish the literature base which encompasses material study, analysis and test experiment on material sample and potential global failures of carcass layer.
- To focus on design, modelling and render static analysis of the carcass layer.
- To design for three different patterns of interlock structure and one design of metal corrugated pipe is static analysed with three different materials of stainless steel grades AISI 304, AISI 316 (SS), Alloy steel (SS) using Dassault system’s Solid works design and analysis software.
- To perform the study on deformation mechanisms and elastic moduli of interlock tube as part of structural analysis of carcass layer.
- To study the property of materials also do practical experiments in laboratory like deformation tests and bending test to study mechanical behaviours and strength of material of corrugated metal pipe and interlock tubes.
- To check the results of the static simulations are good in agreement with the laboratory experiments so that to study on the possibility for adapting corrugated metal pipe design for flexible pipes replacing the carcass layer.

4. Requirements and conditions

- Design of Interlock tube profile designs and corrugated metal pipe tube designs should be done.
- Static analysis should be done using the software Solid works.
- Laboratory experiments like Deformation tests of Interlock tubes and bending curve tests must be performed to check the possibility adaptation of corrugated tube in Flexible pipeline.

5. This task assignment is an integral part of the final project

6. Project submission deadline: 2015 June 1st.

Given to the student Balajee Govindaraj

Task Assignment received ______________________________ ________________________

(*Name, Surname of the Student*) (*Signature, date*)

Supervisor ______________________________ ________________________

(*Position, Name, Surname*) (*Signature, date*)

Govindaraj, B. Modelling and analysis of Interlock and Corrugated tubes for adaptation in a flexible oil pipeline Master of Science final project / supervisor Assoc. Prof. Dr. Marija Eidukeviciute; Kaunas University of Technology, Mechanical Engineering And Design faculty, Production Engineering department.

Kaunas, 2015. 55 p

SUMMARY

This master thesis deals with static analysis, of 2” ID flexible oil pipeline’s carcass layer which is the inner most bore where the fluid flows. The problem in the pipeline is the flow of crude oil inside the flexible pipe. The high temperature and pressure of oil flow inside the pipe and the pressure acting from outside of pipe due to atmospheric pressure sea wave flow causes damage to the carcass layer. This may result damage in other layers which results in spillage of crude oil in the environment especially under sea which is hazardous. Due to rather complicated wall structure where materials with very different properties are interacting, a large number of failure modes are possible. Many of these failure modes are related to design and material properties and selection. In this thesis, the 2” ID carcass layer of a flexible pipeline is described with respect to function, structure, material and possible failure modes are studied. The overall objective of this report is to a give detailed study over the carcass layer failure mode along with respect to function, structure, material and possible failure modes also this paper presents the model designed in solid works simulating the static analysis and predicting the results of displacement, stress, strain and factor of safety for the carcass layer. As a comparative study, a metal corrugated tube which also has flexible nature is modelled and analysed and brought to assumption replacing the interlock tube whether it can adapt the role of interlock tube of flexible pipes.

Keywords: *Carcass layer, static analysis, adaptation, flexible pipeline, SolidWorks*

Govindaraj, B. Spiralinių ir gofruotų vamzdžių modeliavimas ir analizė, jų taikymas lanksčiuose naftotiekio vamzdynuose. Magistro baigiamasis projektas / vadovas doc. dr. M. Eidukevičiūtė; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas, Gamybos inžinerijos katedra.
Kaunas, 2015. 55 psl.

SANTRAUKA

Šiame baigiamajame projekte atliekama statinė 2” ID lankstaus naftotiekio vamzdžio karkasinio sluoksnio analizė. Šis sluoksnis tiesiogiai kontaktuoja su tekančiu skysčiu. Projekte analizuojama problema atsiranda dėl neapdorotos naftos tekėjimo lanksčiu vamzdžiu. Aukšta temperatūra ir slėgis veikia lankstaus vamzdyno pagrindinį – karkasinį sluoksnį, vamzdį iš išorės taip pat veikia slėgis, atsirandantis dėl atmosferinio jūros bangos slėgio. Šie parametrai gali sukelti gedimus kituose sluoksniuose, to pasėkoje nafta gali ištekėti į aplinką jūroje, kas yra ypač pavojinga. Dėl sudėtingos sienelės struktūros, kurioje sąveikauja skirtingų savybių medžiagos, gali įvykti daug įvairių gedimų. Daugelis šių gedimų yra susiję su struktūros ir medžiagų savybėmis ir jų pasirinkimu. Šiame projekte 2” ID lankstaus vamzdžio karkasinis sluoksnis aprašytas ir išnagrinėtas atsižvelgiant į funkciją, struktūrą, medžiagas . Bendras šio projekto tikslas yra išnagrinėti karkasinio sluoksnio gedimus atsižvelgiant į funkcijas, struktūrą, medžiagas ir galimus gedimus. Pateikiamas SolidWorks modelis statinei analizei, prognozuojami karkasinio sluoksnio poslinkis, įtempimai ir saugumo faktorius. Palyginimui buvo sumodeliuotas ir išanalizuotas lankstus metalinis gofruotas vamzdis kaip galimas spiralinio vamzdžio pakaitalas lanksčiuose vamzdytas.

Raktiniai žodžiai: *karkasinis sluoksnis, statinė analizė, pritaikymas, lankstus vamzdynas, SolidWorks*

Contents

Table of Figures

List of Tables

Appendix

1. Introduction

Flexible pipelines are an alternative to conventional rigid steel pipes. These pipelines consists of different layers made up of different materials that act together which enables unique flexibility than rigid steel pipes. The use of flexible pipes has enabled the development of offshore fields which were unfeasible with the use of rigid pipes due to extensive seabed preparation and large dynamic motions. The lack of knowledge and integrity management tools of flexible pipes are the limiting factor that cause pipelines to be replaced before their service life. The critical failure modes for flexible pipes thereby understanding the failures and accessing to the necessary technology for remaining lifetime and calculation of extensive lifetime will be more accurate. The detection of Degradations, deformations and failure mechanisms can be done at an early stage giving the operators a better time to initiate repair measures.

These pipes are slender marine structures which are widely used at offshore applications. These pipelines are constructed with complex multi layered structures which consists of helical wound armour wires or strips combined with concentric layers of metals, polymers, textile, tapes and lubricants which yields a cooperative structure capable of withstanding considerable structural loads as well as internal and external pressure. The flexible pipe technology is continuously developing to cope with new challenges with factors like pressure, temperature and water depth.

The increased research is done in the local and cross sectional structural behaviour of the flexible structures due to the increased utilisation of flexible pipelines in the offshore applications which are coupled with the necessity to predict their critical failure modes. The structural analysis provides the flexible pipelines structure's response to these loads in terms of internal deformations and the stress and strain distribution with the structure's cross section. Static analysis is one of the advanced method to verify the structures, to study and establish the stability, durability and the behaviour of a model in load and constrains conditions.

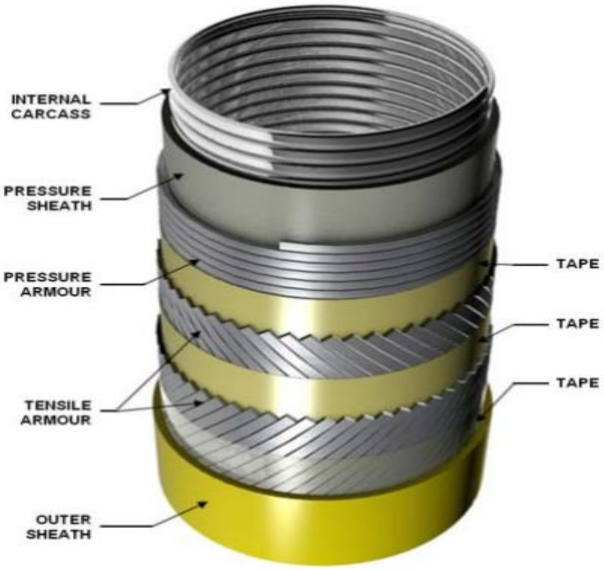


Fig – 1 Structure of Flexible pipe [51]

1.1 Description of Carcass layer The carcass is the innermost layer of a pipe, and the only metallic component that is in direct contact with the fluid in the bore. The carcass is made from stainless steel strip in a continuous process onto a mandrel that needs to be compatible with the chemical constituents of the transported liquids and/or gases.

Generally, carcass is made up of cold forming thin steel ribbons into interlocked flexible structures. Normally this structure will undergo limited stresses and get more exposed to erosion or corrosion in case of sand or undesired chemicals flow. Inaccuracies in the design or load conditions that change the carcass performance has been the main reason for carcass fatigue. Recent experiences shows that the carcass may see significant stress levels. Normally a fatigue crack in the carcass should not be experienced, even though it leads to the loss of integrity for the flexible pipe. A complex interaction with other layers is also one main reason for getting a pipe damage developing into a pipe failure.

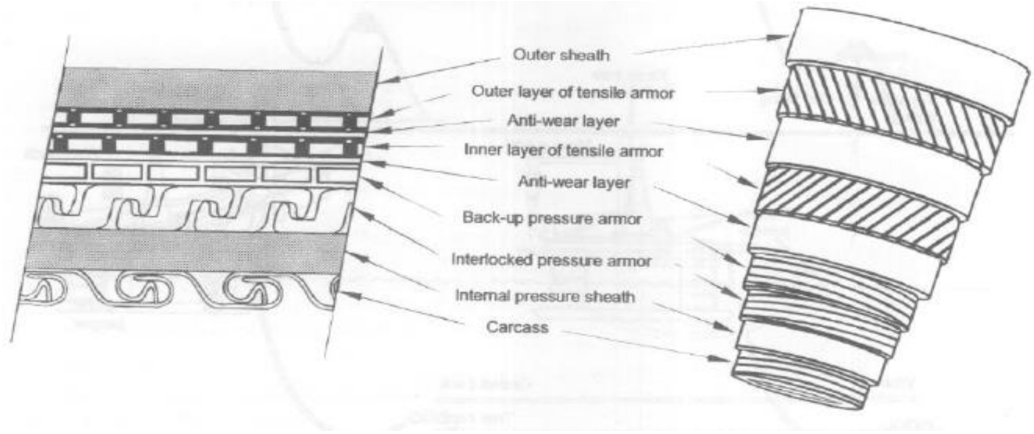


Fig – 2 Construction of Flexible pipe [52]

The carcass provides strength against external hydrostatic pressure, and mechanical protection of the liner against pigging tools and abrasive particles. It also provides strength to resist crushing loads during e.g. installation operations. At large water depths the hydrostatic as well as the crushing loads will increase. The carcass is an open structure and does not provide any containment of internal pressure, i.e. oil and gas can flow freely across the carcass. Flexibility is defined as the ability of each profile to slide with respect to the adjacent profiles. In the case of a damaged outer sheath, the external pressure will be acting directly onto the liner, and must be carried by the carcass alone.

Fig – 3 Cross section view of carcass layer [53]

1.2 Function of Interlock tubes

- Prevention of rupture of elastometric liner during rapid internal depressurisation.
- To support radial inwards loading resulting from the response of the reinforcement cable layers to overall tension, torsion or bending of pipe.
- To resist point and distributed loads including external pressure.

1.3 Description of Corrugated metal pipe Corrugated steel pipes (CSP) are widely used for gravity structures because the corrugated shape has a much larger moment of inertia that offers greater stiffness with less material in structures. For flexible pipes, including corrugated pipes, deflection is the most important performance limit, although corrugated pipes behave slightly differently than general flexible pipes. Figure 5 shows the profile and dimensions of the corrugated pipe considered in this study, and the corrugations are measured from crest-to-crest (pitch) horizontally and valley-to-crest (depth) vertically. The values of the pitch, depth, and thickness vary in the three-dimensional analysis parametric studies. The relationship between factors, such as pitch and depth, is needed to model pipe corrugation because they are not independent.

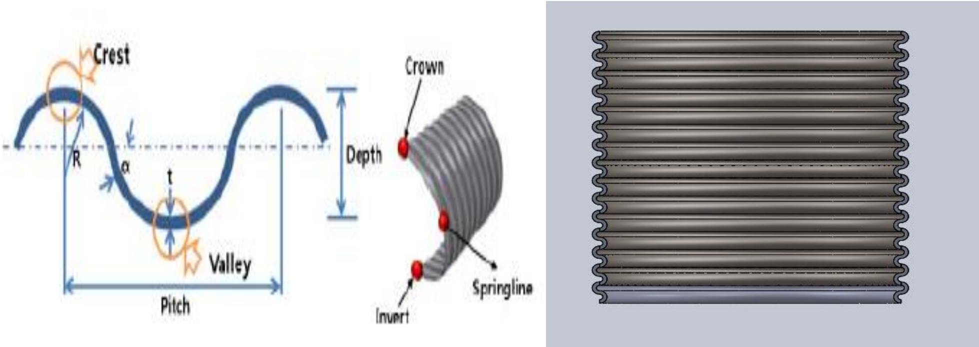


Fig – 4 Section of a corrugated pipe [18]

2. Literature analysis on the circumstances of carcass failure

2.1 Why static analysis? The first application of flexible pipe was static application. Flexible pipe, wholly or in part, resting on the seafloor or buried below the seafloor, and used in a static application. Also the flexible pipeline is installed on the seabed and is not subjected to large and frequent movements, hence it can be referred to as a static application. For static sea bed lines protection by trenching and rock dumping special considerations must be made to avoid buckling. For static flowlines this failure mode has been experienced. This situation is used for grounding assumptions in our case study. The behaviour of our pipe's inner most layer interlock tube when the pipe is over the sea bed.

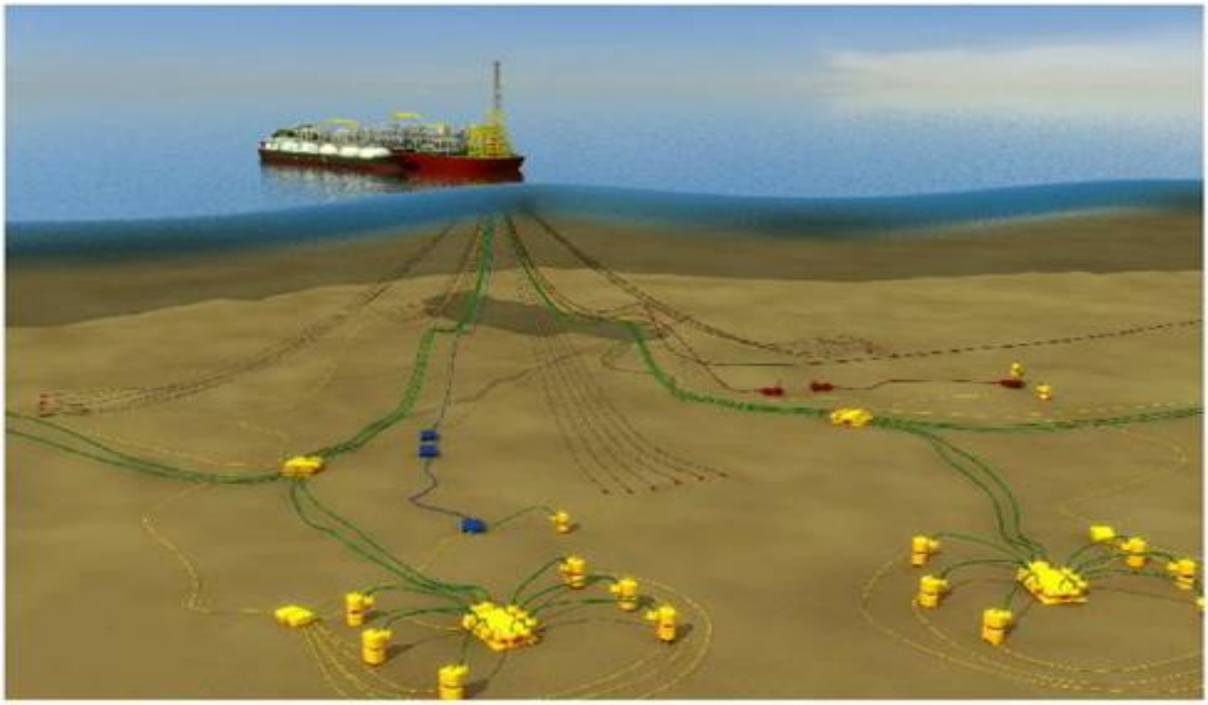


Fig – 5: Flexible Pipelines over sea bed – Static application [53]

Static analysis is one of the prime analysis for flexible pipeline design analysis. A common use of Static analysis is for the determination of stresses and displacements in mechanical objects and systems.

Static analyses of piping systems is within the piping discipline commonly referred to as pipe stress analysis or just stress analysis. To validate the structural integrity of piping systems the piping structural engineers (pipe stress engineers) performs different types of analysis dependent on the criticality, design code, international-and national regulations, load-cases and any specially request from customers such as optimisation with regard to total assembly- weight and volume. Piping stress analysis is by international and national piping design codes more or less limited to static analysis.

Static analysis is the analysis carried out in order to find the sustained (primary) stresses, displacement (secondary) stresses, pipe support loads and equipment loading due to loads caused by the internal static pressure, and other sustained and displacement loads. Static analysis is considered mandatory for all piping systems requiring a comprehensive analysis. This analysis is usually not time consuming.

2.2 Failure modes of carcass layer The number of potential failure modes in static application for an interlock tubes are high. The complete list of potential failure mechanisms for static applications listed below.

Global failure	***Potential failure mechanisms***
Collapse	Collapse of carcass due to excessive tension Collapse of carcass due to excess external pressure Collapse of carcass due to installation loads or ovalisation due to installation loads.
Tensile failure	Collapse of carcass due to excess tension
Over bending	Collapse of carcass
Torsional failure	Collapse of carcass
Erosion	Collapse of carcass
Corrosion	Collapse of carcass.

Fig – 6: Failure mode of Carcass Layer [39, 53]

Collapse of the carcass layer of flexible pipeline occurs when the carcass fail by collapsing inwards which cause severe problems for flow of fluids. Collapse also occurs due to excessive external pressure. Deepwater installation under deep water may experience hydrostatic pressure may contribute to collapse due to improper construction. Manufacturing defects like high initial ovality and high radial gap may cause collapse. The factors like the dropped objects, collisions, and other unexpected forces during transportation and installation are also the critical phases of carcass layer to get collapsed. Also the collapse capacity of carcass strongly depends on the supporting structures or whether there is a gap. Several mechanisms like stretching and possibly deformation of carcass due to gravity may even cause collapse. Since carcass is made from metal strip of cold forming process; the given material which fails to meet the technological limitations with regards to thickness of strip may cause failure of carcass. The collapse of strength of carcass which is determined by the stiffness of the carcass profile (moment of inertia) has a basic limitation for this reason.

Burst is said to be the opposite of collapse which is caused by the internal pressure or excessive forces and the materials get rupture outwards. This type of failure may be caused even by the fault in engineering and fabrication of the pipe, faults in pressure operation and operations above design limits. Opposite of collapse, burst is caused by internal pressure or excessive forces and the materials will rupture outwards. Two potential failure mechanisms leading to burst is rupture of tensile or pressure armour due to excessive internal pressure. These failures may be caused by fault in engineering or fabrication of the pipe, fault in pressure integrity modules upstream in the system and operating above design limits. The burst resistance gets decreased due to fabrication errors, internal corrosion, erosion or external abrasion creating weak spots.

Tensile failure in static flow lines occurs due to snagging by fishing trawl or ship anchors. Excessive tensile forces will tighten the carcass layer and act as compression over it leading to the collapse of carcass layer.

Compressive failure occurs during pipeline installation, the temperature of the pipeline materials are balanced with the temperature of the ambient water. At the beginning of production, warm gas and fluids conveyed in pipeline rises the temperature causing the material of the pipeline especially steel metal parts to expand. During the case of expansion, if it is restricted by friction or constrained ends compression forces build may cause buckling and over bending. The static lines in special cases undergo radial buckling known as bird caging. This phenomenon occurs when the compressive loads are large enough to cause wire steel interlock disorders.

Over bending of the carcass happens due to the compression force on one side and tension force on the other side of the pipe also ovalisation reduces the collapse resistance. Large bending forces results in unlocking of interlock layers of flexible pipe which reduces the pressure and tension resistance of carcass too.

Torsional failure occurs in the flexible pipes in various depths under sea water.The pipes are in constant motion due to wind, waves and currents. Torsional force in either direction on the carcass will get tighten and collapse. Also the torsional force created to restore equilibrium causes increase compressive force risking the collapse of carcass.

Fatigue failure occurs during operation, the carcass layer may experience different stresses which can be tension, compression, torsion corrosion and temperature variations. The fatigue failure mostly occurs due to accumulated cycles of load above mentioned stresses which wears down the carcass layers. Also it occurs rarely due to other factors like manufacturing faults where the carcass interlock strips fails to slide when they are fully expanded or compressed causing an unintended distribution of force which results in fatigue damage.

Collapse of carcass due to gas permeation occurs due to the gas in the bore under high pressure gets diffuses into the polymer liners and gets solved with the polymer. It is a very slow process which may take several weeks up to few months to reach a steady state condition. A large amount of gas which gets solved with polymer material will get pressure up between the liners creates a pressurised gap when the bore pressure is reduced. During high operational bore pressure, the enough gas in the polymer diffused into the gap and builds up a gas pressure at interface results in collapse of carcass during the bore depressurisation.

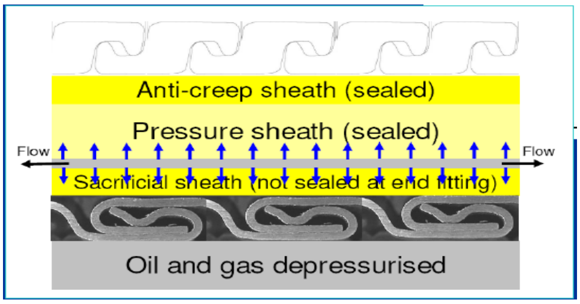


Fig – 7 Gas permeation over carcass [53]

Erosion in carcass layer occurs when the particles in the fluids flowing through the carcass layer collides with the internal wall of carcass due to over time it causes thinning of steel carcass layer. When the solid particles like sand are conveyed through the pipe can create corrosion problem whereas, for the gas flow lines the solid particles have high velocity and collide with inner wall of carcass. The main cause for failure of pipeline is not only the erosion but also the process erosion wears down the corrosion protecting layer of the internal carcass layer wall which eventually results in thinning of carcass causing collapse and rupture.

Corrosion in carcass at the end fitting interface will not cause damage to sealing barrier or locking mechanism. The corrosion of steel layers is caused by the chemical reaction in the material which gradually causes destruction in the material and reduces resistance and fatigue life. A typical reason for corrosion of pipeline is when the seawater gets saturated with oxygen and comes in contact with steel layers induces oxidation. Corrosion by itself is not only a normal cause to pipe failure but together with high loadings or fatigue loads is also a serious threat of integrity. The internal corrosion of carcass could be identified if the corrosion protection on the internal wall of the carcass getting eroded away.

2.3 Study on deformation mechanisms of interlock tubes

The deformation mechanism on elongation When a pipe is stretched, it will elongate and the amount by some stretch is ΔL. According to the loading mechanism, the deformation of interlock occurs is axial deformation. ΔL denotes the result of both sliding action and deformation of turns is illustrated in figure 9 below. The amount of turn i+1 relative to turn i, which is a rigid body motion, can be identified as $S_i = g_i - g_{i.}^2$

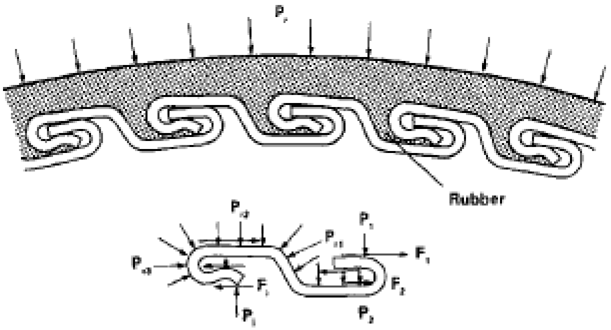


Fig – 8 Forces exerted on the interlock tube under pipe bending [7]

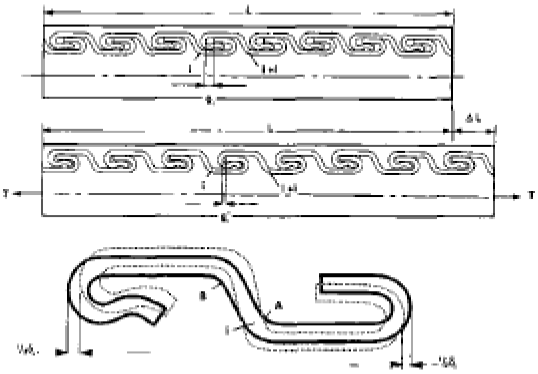


Fig – 9 Forces exerted on the interlock tube under pipe elongation and tension [7]

The resulting displacement of turn in axial direction due to deformation can be given as,

$$\frac{1}{2}\delta_i + \frac{1}{2}\delta_i = \delta_i \qquad - (1)$$

Therefore,

$$\Delta L = \sum S_i + \sum \delta_i \quad - (2)$$

$\sum \delta_i$ and $\sum S_i$ are denoted as the function of pipe global tension T. When the tension is small, the deformation $\sum \delta_i$ which depends largely on upon the interface friction forces enhanced by the radial inwards loading which can be too small to cause fatigue problems. Even though when a tension reaches a certain level, the deformation could be appreciable.

When the pipe is under bending, the mechanism becomes more complicated. According to the loads, acting upon a turn of the interlock it is possible for the turn to deform either as shown in figure 10.

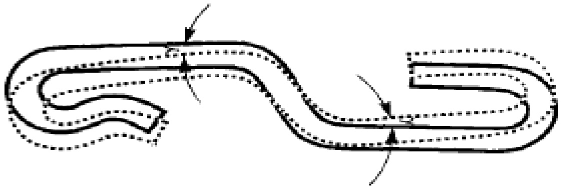


Fig – 10 Bending mode of interlock deformation [7]

The above two cases is referred as tensile and bending modes of interlock deformation. Slip is also possible during bending deformation. When an interlock turn is considered to deform in the manner as shown in figure 10**,** a threshold bend radius can be identified and the critical strain can be calculated as a function of the applied bend radius of the pipe and some parameters relating to the interlock geometry.

The interlock on convex side is subjected to tension; it is natural to consider that the individual turns are deformed in a way similar to that described for the case of tension such that interlock is deformed in a tensile mode. However in this case the slip and the elongation of the turn will not be circumferentially uniform. Moreover the relative proportion of the slip and the elongation which compromise the total axial extension of the interlock is expected to be different from that for the case of tension. This is due to the difference in loading mechanism.

Prediction of fatigue life Interlock tubes undergo stresses and strains causing fatigue cracking which can be evaluated as a function of the overall applied pipe loading or bend radius. To calculate the stresses due to pipe tension, the pressure and forces should be noted. The radial pressure can be calculated using existing cable and wire rope theory. The determination of the intrusion pressure, interface reaction forces and friction forces is by no means an easy task. The determination of intrusion pressure is complicated mainly because of the complex process of intrusion of the rubber and sliding action of the adjacent turns of the interlocks. The difficulties involved in finding the interface reaction forces and friction forces are largely due to the uncertainties about the points of action of forces. From this itself we could able to identify how difficult and complex it is to evaluate the stress in the interlock due to pipe bending.

In order to avoid difficulties and complexities an alternative approach can be handled to assess the effect of fatigue loading imposed upon the interlock. This approach concerns the deformations (strains) instead of stress developed in critical sections of the interlock as it responds to the overall applied tension or bend radius. Three different cases i.e. pipe under tension, pipe under bending and the combination of the two will be considered separately.
Figure 11 gives the geometrical parameter of interlock.

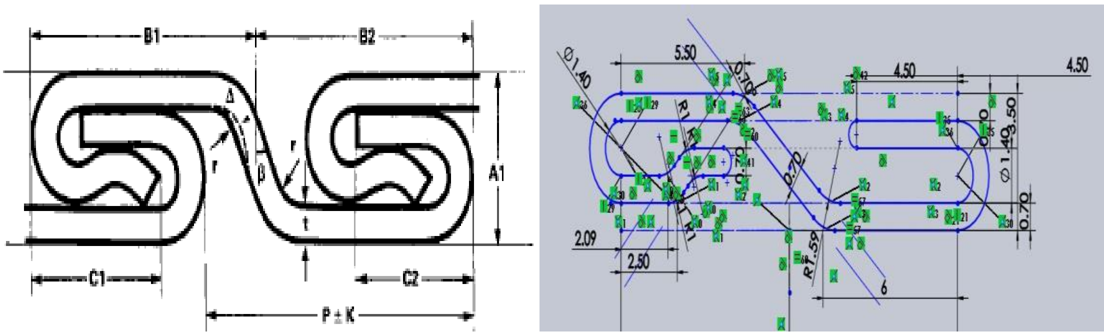


Fig – 11 Key dimensions of Interlock section [7]

Pipe under tension The analysis if the deformation mechanism described previously the approach to assume the elongation δ_i is known, and then work out the strains in the critical sections corresponding to this elongation. Later on the relationship between δ_i and the applied tension will be established by considering the global axial stiffness, the interlock geometry and the amount of sliding motion. Finally, some interesting special cases will be discussed in conjunction with the formulae derived.

Strains corresponding to δ_i Consider that a turn of the interlock would deform in the manner in figure 8. Because the radii of curvature at A and B are same, the strains at these areas should be identical and thereafter it will suffice to analyse the strain at B.

To calculate the strain at B corresponding to an elongation δ_i of turn i, the following assumptions have been made:

i) The three dimensional problem of the tube may be treated as two dimensional.
ii) The elongation is only due to the deformation of the central part of the turn.
iii) The deformation at the central part may be characterised by the change of angle β.

Deformations are small, $\sin\Delta\beta \approx \Delta\beta$, $\tan \Delta\beta \approx \Delta\beta$ and $\cos(\beta + \Delta\beta) \approx \cos\beta$.

Referring to figure 9, it can be seen that the elongation of the left half of the turn shown in figure 11; will be $0.5\delta_i$ and the change in angle β is given by

$$\Delta\beta = \delta_i / A_1 \qquad (3)$$

The change in angle Δβ, the strain in question can be given as**,**

$$\varepsilon = \frac{(SS_1 + t.\Delta\beta) - SS_1}{SS_1} = \frac{t.\Delta\beta}{SS_1} \qquad (4)$$

Where SS_1 is the length of the arc corresponding to angle (90 – β) that is,

$$SS_1 = \frac{(90° - \beta)}{180°} . r \qquad (5)$$

Substituting equations (3) and (5) in (4), we get

$$\varepsilon = \frac{180t}{\pi r A_1 (90° - \beta)} . \delta_i \qquad (6)$$

This equation gives the strain at critical area of the interlock corresponding to an elongation δ_i of turn i. It demonstrates how the interlock geometry (thickness t, radius r, section depth A_1 and angle β) affects the strain and hence the fatigue performance of the interlock tube.

Relationship between δ_i and applied pipe tension According to equation 2, if the elongation of the ΔL of the pipe and the total amount of slip $\sum S_i$ of the interlock are known, the summation of all elongations of the individual turns can be determined by

$$\sum \delta_i = \Delta L - \sum S_i \qquad (7)$$

The elongation of the pipe under tension T may be related to a pipe axial stiffness parameter G which is axial deflection per unit load multiplied by length of pipe L.

$$\Delta L = T\,L/G \qquad (8)$$

G can be obtained either by theoretical analysis or from experiment.

The amount of slip of turn i + 1 relative to turn i, $S_i = g_i - g_i'$ is a function tension T for a specific pipe. For different pipes, the geometry and clearances of turn i and turn i + 1, the roughness (friction coefficients) of the interfaces and the positions of the leg ends of the turns can all affect S_i. This makes it extremely difficult to evaluate theoretically the total amount of slip, $\sum S_i$. For this reason, an experimental method has been developed to measure the slip function and this will be described briefly later. An empirical formula for $\sum S_i$ with the form,

$$\sum S_i = S_t(T).L \quad (9)$$

can be denoted as particular size of the pipe. $S_t(T)$ is the amount of slip per unit length of the interlock tube also function of tension T for a given pipe. With ΔL and $\sum S_i$ being expressed as in equations (8) and (9), the relationship between δ_i and applied pipe tension is given by,

$$\delta_i \approx \frac{1}{n}\sum\delta_i = (\Delta L - \sum S_i)/n = \left(\left(\frac{T}{G} - s_t(T)\right).L\right)/\,n \qquad (10)$$

Where n is the no of turns in length L of the interlock tube, which can be found by knowing the interlock pitch P and length of the pipe i.e.

$$n = L/P \qquad (11)$$

therefore,

$$\delta_i = \left(\frac{T}{G} - s_t(T)\right).P \quad (12)$$

which gives the elongation per interlock turn corresponding to the applied pipe tension.

Relationship between ε_A and overall pipe tension T This relationship can be obtained simply by substituting equation (12) into equation (6)

$$\varepsilon_A = \frac{180.t.P\left(\frac{T}{G} - s_t(T)\right)}{\pi r A_1 (90° - \beta)} \qquad (13)$$

Using this equation along with fatigue data for the interlock tube, it is possible to assess the effects of the interlock geometry and pipe tension upon the tensile fatigue resistance of the pipe.

Bending behaviour Bending is one of the most important property of flexible pipe comparing to ordinary rigid steel pipes. Especially for carcass inner most layer this property is ensured. Similar procedures to those in the preceding section will be employed to describe the deformation approach for calculating the interlock deformations while the pipe is under bending. As a relationship between the critical strain and the elongation of the turn has already been established and it is necessary to develop the formulae for δ_i and ε corresponding to the applied bend radius as shown in figure 12.

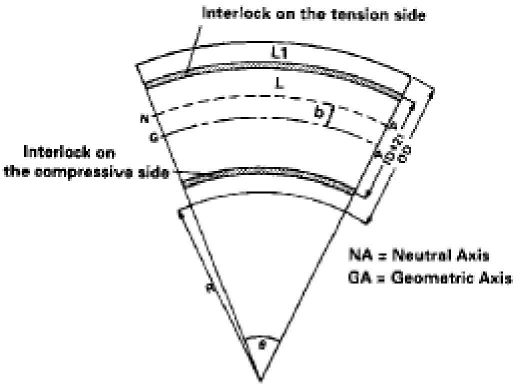


Fig – 12 Geometry of interlock tube under bending [7]

Relationship between δ_i and applied bend radius Assume the pipe of length L is bent to radius R as shown in figure 28. It can be easily seen that,

$$L = [R + (OD/2) + b]\,.\theta \qquad (14)$$

$$L_1 = [R + (OD/2) + (ID + 2t) / 2]\,.\theta \qquad (15)$$

Also the tube has got extended, so

$$\Delta L = L_1 - L = [(ID + 2t) / 2 - b]\,.\theta \qquad (16)$$

And, since θ = L/[R + (OD/2) + b] then:

$$\Delta L = L.\,\frac{ID + 2t - 2b}{2R + OD + 2b} \qquad (17)$$

Combining above equation 17 with equations (7), (9) and (11), we get an expression similar to equation (12) for δ_i is obtained.

$$\delta_i = \left(\frac{ID+2t-2b}{2R+OD+2b} - S_b(R)\right).P \ (18)$$

where the slip function S_b (R) has a similar meaning to S_t (T) used in the case of tension but is a function of bend radius R instead of tension T. As can be seen from the above formula, the elongation of the turn is not only dependent upon the applied bend radius, but also the function of the position of the neutral axis of the bent pipe.

Relationship between ε_A and applied bend radius The relationship between the critical strain and the corresponding bend radius can be obtained simply by substituting equation (18) and into (6) which gives,

$$\varepsilon_A = \frac{180t.P.\left(\frac{ID+2t-2b}{2R+OD+2b} - S_b\ (R)\right)}{\pi r A_i(90-\beta)} \quad (19)$$

The exact forms of slip functions S_t (T) and S_b (R), which have been defined as the amount of slip per unit length of the interlock tube, have to be determined by experiment for each pipe size. This may seem to be a disadvantage, particularly when it is recognized that the function maybe different for different pipe sizes and even for one size the production variations may cause S_t (T) and S_b (R) vary.

2.4 Elastic moduli of carcass The unbonded flex pipe of 8 layers except carcass are assumed to have isotropic property. Specifically carcass show orthotropic. The effective elastic moduli have carcass layer have been developed in terms of the influence of deformation to stiffness. With the consideration of elastic moduli the structure can be properly analysed. Since the structure of carcass is very complex in structure, the response is extremely difficult to analyse. So it is suggested to limit the scope of applicability due to simplifying assumptions on which they have been based. Neglecting frictional effects is among the hypothesis commonly made.

The carcass layer is a metallic structure which mainly resists radially inward forces providing the partial resistance to collapse of the layers when the pipe is subjected to various types of external loadings. The layer of interlock is almost a circumferential lay. The carcass is an orthotropic layer and is not in regular shape and so the effective moduli are not the material moduli. The effective elastic moduli are analysed as E_x, E_y and E_z where the subscripts x and y are the directions of the plane and z is the direction perpendicular to the plane.

Effective Modulus of z direction The stiffness of the equivalent orthotropic shell according to De 'Sousa et al. (2009) have been given by,

$$(EA)_s = h_s.E_z \text{ , and } (EI)_s = (h_s^3/12)\cdot E \qquad (20)$$

Where $(EA)_s$ and $(EI)_s$ are the membrane and bending stiffness of the orthotropic shell respectively and $h_s$is the effective thickness. According to the above equation, the effective modulus of z direction can be calculated. h_s and E_z are unknown variables.

Effective modulus of x direction The equivalent shape of one carcass element under the stress of σ_x is shown in figure 13(a). It is assumed that the internal of one carcass element is rectangular as per design – 2 in our case. The analytical model of the effective modulus of x direction is given.

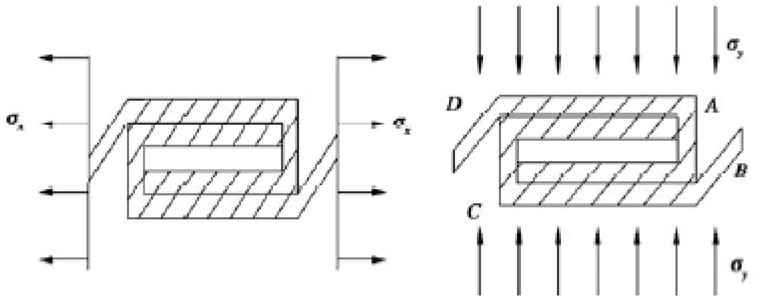


Fig – 13(a) **Fig – 13(b)**

Equivalent format of carcass element [45]

The deflection of the slope edge caused by the force of x direction is,

$$\delta_{p1} = \frac{5pl^3 sin\theta}{48E_s I}\ (I = \frac{1}{12}bt^3) \qquad (21)$$

Where P is the force of x direction and b is the width of the carcass, which equals to 1; t is the strip thickness.
The deflection of the slope edge caused by the bending moment of x direction is,

$$\delta_{\mathrm{M1}} = \frac{\mathrm{Ml}^2}{8\mathrm{E_s I}} = \frac{\mathrm{P}l^3 sin\theta}{16\ E_s I} \qquad (22)$$

The elongation of the slope edge caused by the force P is,

$$\delta_2 = \frac{Plcos\theta}{2E_s t} \qquad (23)$$

The elongation of the whole rectangular is,

$$\delta_3 = 2\frac{Pl\prime}{Et} + \frac{Pl\prime}{2Et} = \frac{5Pl\prime}{2Et} \qquad (24)$$

The equivalent strain of x direction is

$$\varepsilon_{\mathrm{x}} = \frac{(\delta_{P1} - \delta_{M1})sin\theta + \delta_2 cos\theta + \delta_3}{l + l\prime} \qquad (25)$$

Then the effective modulus of x direction is

$$\mathrm{E_x} = \sigma_x / \varepsilon_{\mathrm{x}} \qquad (26)$$

Effective elastic modulus of y direction In carcass layer pressure will affect its function and the state of stress is shown in the figure 13(b). Only AB and CD will have the effect and cause deflection. The slope edges will not affect.

The elongation of the AB and CD are the same and the total value is

$$\delta = \frac{Wl}{2E_s t} \qquad (27)$$

Where W is the force of y direction and t is the strip thickness.

The equivalent strain of y direction is

$$\varepsilon_{\mathrm{y}} = \frac{\delta}{l} = \frac{W}{2E_s t} \qquad (28)$$

Then the effective modulus of y direction is

$$\mathrm{E_y} = \sigma_y / \varepsilon_{\mathrm{y}} \qquad (29)$$

The orthotropic property and irregular cross section of carcass layer takes the account of effective elastic moduli as mandatory. The influence of deformation on structure stiffness is observed on analytical model and consecutively effective elastic moduli is obtained which solves the problem that there is no existing methods are available for the calculation of effective moduli.

2.5 Study of Value analysis Systematic identification and elimination of unnecessary cost resulting in the increased use of alternatives, low cost material, cheap designs, less costly methods of manufacturing etc. to provide the same quality, performance and efficiency of the material or method which results in decrease of overall costs and consequently greater profits. Value analysis is one of the major techniques for cost reduction and prevention. It is also known as Value engineering (VE), Value assurance (VA) and Value management (VM). This is a disciplined approach which ensures the necessary functions at minimum cost without comprising on quality, reliability, performance and appearance.

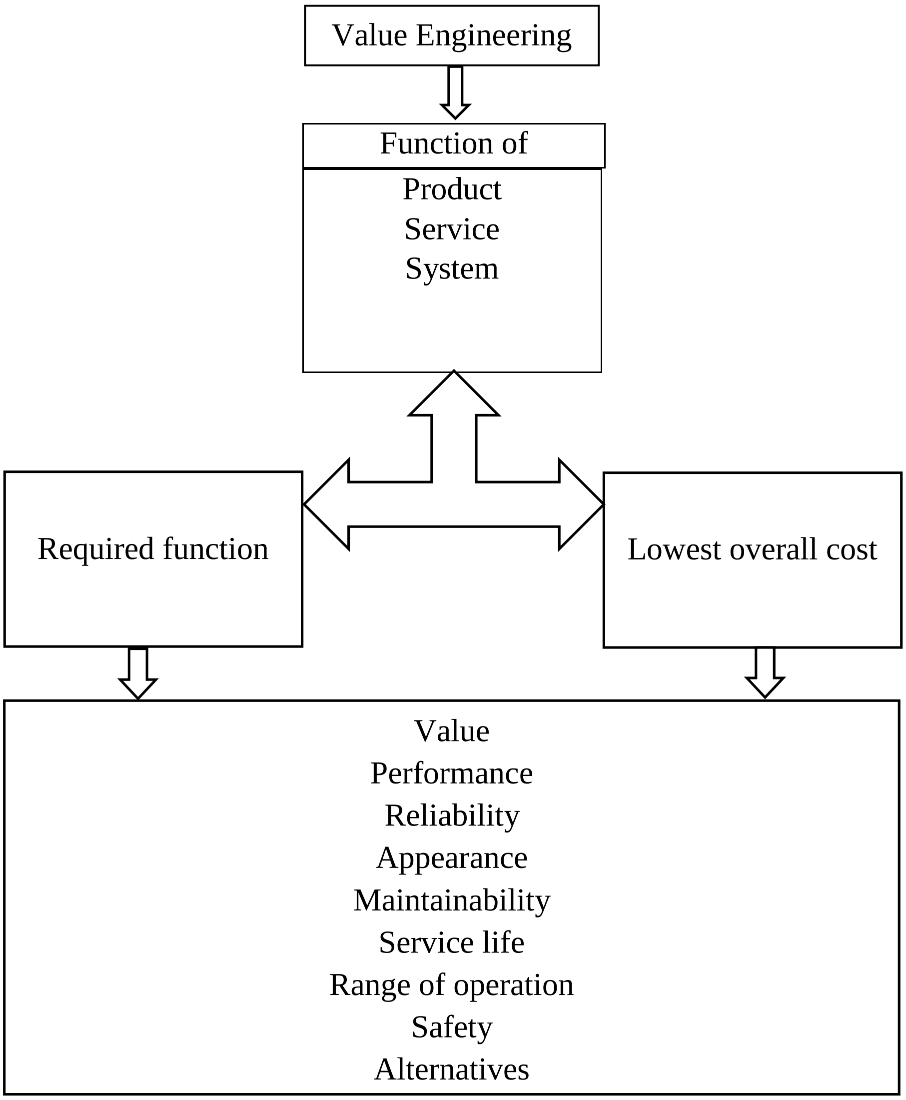


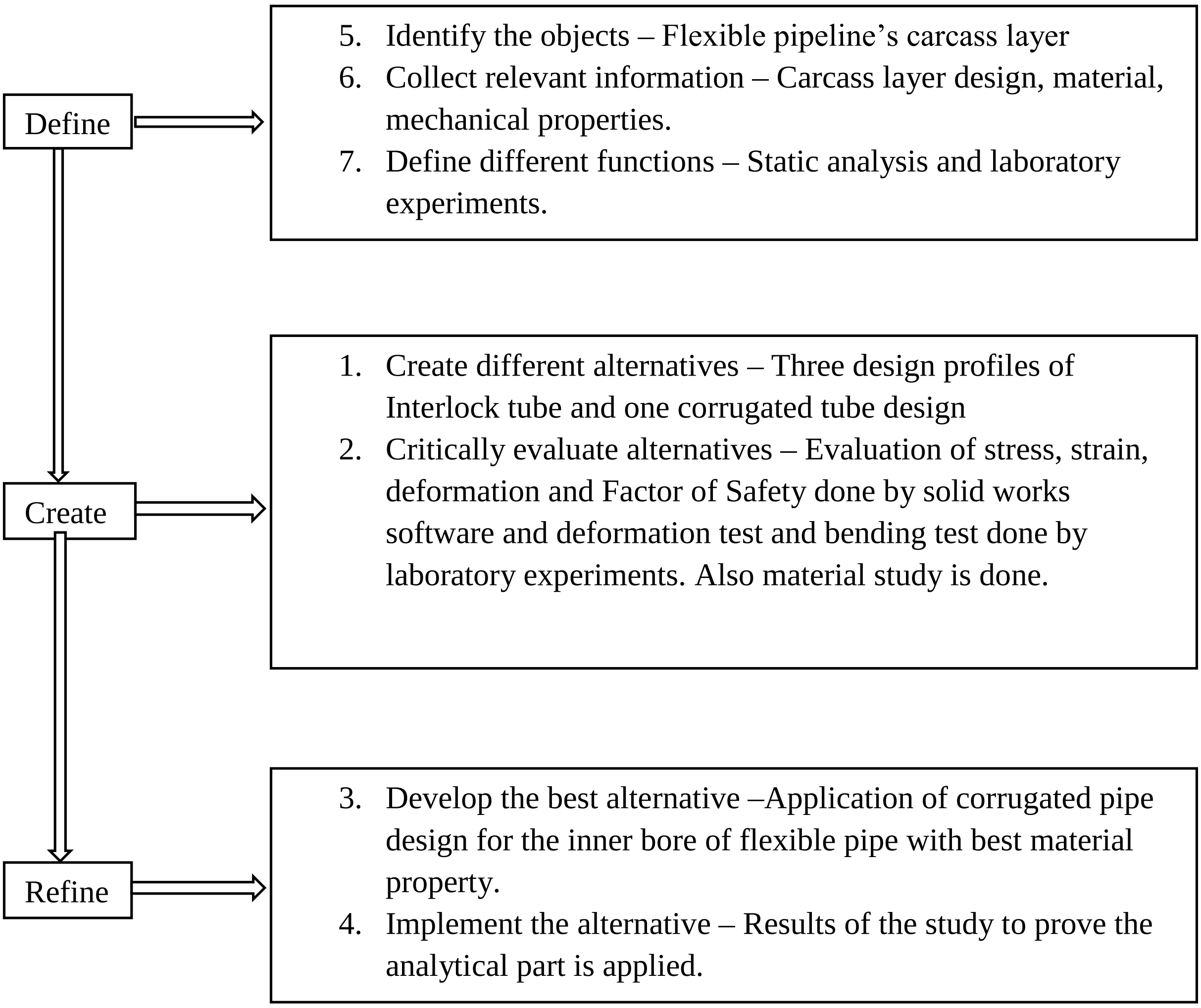
Fig – 14 Value analysis [50]

2.5.1 Functions of Value analysis Function is the factor which makes a product useful. The value of the product is its functional utility. The types of functions are as follows:
Primary function is the basic functions which the product is specially designed to perform.

Secondary function is the function which if deleted would not prevent the device from performing its primary function. ***Tertiary function*** are usually related to esteem appearance.

2.5.2 Value Analysis Vs Value Engineering Value analysis and value engineering are used synonymously, which are different between them. The difference lies in the time and the phase of product life cycle at which the techniques are applied. Value analysis is the set of application of techniques to an existing product in the perspective of improving its value. It is also called as remedial process. Value engineering is the application of exactly the same set of techniques to a new product at design stage itself. It is called as preventive process.

2.5.3 Application of value analysis in our case study



5. Identify the objects – Flexible pipeline’s carcass layer
6. Collect relevant information – Carcass layer design, material, mechanical properties.
7. Define different functions – Static analysis and laboratory experiments.

1. Create different alternatives – Three design profiles of Interlock tube and one corrugated tube design
2. Critically evaluate alternatives – Evaluation of stress, strain, deformation and Factor of Safety done by solid works software and deformation test and bending test done by laboratory experiments. Also material study is done.

3. Develop the best alternative –Application of corrugated pipe design for the inner bore of flexible pipe with best material property.
4. Implement the alternative – Results of the study to prove the analytical part is applied.

III. Methodology of thesis

To establish an overview of the flexible pipe especially carcass layer i.e., the interlock tube and literature survey on its failure mode is done. Using Solid works software the interlock tube is designed and static analysis is done using application of various grades of stainless steel material and three different designs of interlock profiles also metal corrugated design profile to find out which design and material can withstand stress, strain and undergo deformations The metal corrugated pipe which has flexibility nature like carcass layer were designed in solid work software and analysed to study the stress, strain and deformations for the possibility of adapting in flexible pipe replacing carcass layer. Bending test were taken using the specimen of metal corrugated pipe and deformation test was performed over interlock tube specimens to find out the mechanical behaviour of pipes. This experiment methodology is to represent durability and damage tolerance in carcass steel and corrugated pipe. Refer API standard reports in combination with flexible pipeline industry manufacturing standards, will give a basis for understanding design and material characteristics of carcass layer. Conference papers, journals and text books will provide further knowledge over mechanical and structural behaviour of carcass layer and corrugated metal pipes.

IV. Analytical part

4.1 Analytical description

- Pipe design optimized with retaining the key features of traditional flexible pipe.
- Mechanical properties of carcass layer under loading / bending are addressed.
- In addition pipe stress strain analysis are presented with various load cases.
- Largely complies with requirements of API's document with minor variations.
- Theoretical result will be used to compare with the model result.

Flexible pipe widely used in deep sea oil industry for its capacity dealing with large deformation and displacement. To achieve the advantage of flexible pipelines require complicated inner structure i.e. Carcass layer and difficult to analyse. One of the correlative disadvantage is difficulty of understanding the mechanical behaviour of carcass particularly under deep water.

In our case study, the analytical study of carcass is can be done by using two current methods:

i) Analytical method
ii) Numerical method.

In past many analytical studies were on this subject by researchers. However, all the studies i.e. analytical methods have many simplified assumptions inevitably which significantly limit the application range of results.

Model designed in this thesis for analysis includes the main features of interlock tubes and corrugated pipes with very little simplifying assumptions. Also the model considers the contact interact, geometric non linearity and friction has been employed to accurately simulate the structural behaviour of carcass. On the other hand, the analytical parts are quite complicated due to large non linearity of the complex in structure and design. So the study is done with the help of design and analysis software Solid works; using that a similar model is designed and analysed with main features of carcass layer with very little simplification. And numerical behaviour of carcass under three load condition is obtained.

In this thesis, we focus on design criteria, carcass deformation and disorganisation or loading of interlock tube as well as fatigue and wear. The special purpose for modelling the interlock tube is to study the structural response of the pipe being laid. The pipeline is made up of steel layers. To avoid the above failures or to increase the life period, the interlock tube has to be designed in such a way based on below criteria. The recommended design criteria is based on API standard 17B.

4.2 Design criteria for carcass as per API standard 17B Design of flexible pipes involves advanced materials, interaction between very different materials in a complicated structure and time dependent degradation mechanisms. It is identified a large potential for increased robustness by improving the completeness of operational design of flexible risers and pipeline systems. The field experience on flexible risers and flow lines indicates that the design basis has been insufficient. The statement of insufficient design is based on experience from failure investigations, showing that the stress/loads in many cases have been under predicted relative to the maximum allowable design stress/loading. This is often combined with wrong predictions of degradation- and failure mechanisms. New and unexpected failure modes have been experienced, in many cases related to material properties and degradation or failure mechanisms. Development of more accurate tools for design and life prediction by means of numerical simulations combined with new test methods, full scale testing, instrumentation and monitoring during operation and field experience in general should have had more focus.

The design of the internal carcass shall account for the following:
a) Design of flexible pipes involves advanced materials, interaction between very different materials in a complicated structure, and time dependent degradation mechanisms.
b) Collapse with minimum specified internal pressure, maximum external pressure, maximum pipe ovality, and pipe bent to an agreed bend radius and pipe wall thickness. The external pressure shall be either the full external pressure acting on the outside of the internal pressure sheath or the maximum annulus pressure if this exceeds the external pressure.
c) Fatigue in the carcass strips;
d) Crack growth along the carcass strip due to bending-induced stresses in interlocked spirals. The carcass design shall be in such a way that crack growth shall not occur.
e) Loads induced by thermal expansion and contraction, and/or swelling of the internal pressure sheath;
f) Erosion and corrosion
The utilization of the internal carcass depends on three water-depth ranges. Buckling failure modes should be evaluated for the carcass, and the layers must meet the design requirements.

4.3 (ISO 2006) design requirements for internal carcass

a) Collapse with minimum specified internal pressure, maximum external pressure, maximum pipe ovality, and pipe bent to an agreed bend radius. The external pressure shall be either the full external pressure acting on the outside of the internal pressure or the maximum annulus pressure if this exceeds the external pressure.
b) Fatigue in the carcass
c) Crack growth along the carcass strip due to bending-induced stresses in interlocked spirals. The carcass design shall be in such way that crack growth shall not occur.
d) Loads induced by thermal expansion and contraction, and/or swelling of the internal pressure sheath.
e) Erosion and corrosion.

The main problem of carcass is more of design weakness. Taking the account on above design criteria and grounding assumptions as static applications, three different designs of interlock tubes were designed using Solid works software. These tubes were made to undergo static analysis to find out their rigidity and three different material study were made which are used by the manufacturers. A comparative study have be done to find out which interlock tube design is better. Also an experimental study on adaptation of metal corrugated pipe is done by modelling and simulating static analysis, to check that it can be applicable for flexible pipes in static application.

4.4 Design and Structural analysis of carcass layer and corrugated metal pipe using Solid works software A modelling of the pipe interlock tube and metal corrugated pipe has been designed and static analysis have been done to study the structural response of the pipe. This carcass layer of flexible pipeline is generally made up of steel and its alloys will basically govern the load response. For this static analysis, the factors like internal and external pressure and temperature are considered. The only reason to consider the above factors are the pipeline will be laid on sea bed experiencing high water pressure. The analysis are grounded based on assumptions that the flexible pipeline is laid on the sea bed which means the external pressure is 10 MPa and temperature is 30°C are only considered; gravity is ignored (for cross section analysis) assuming pipe empty.

4.5 Pipe specifications

The 2 inch ID pipe is chosen for the case study which is of complex structure. The profile of all pipe is uniformly 0.7 mm thick and length of tube. The geometric and material properties and cross section of carcass can be seen below. Some data is subject to uncertainity.

4.6 Pipe designs

4.6.1. Interlock tube profile design - 1

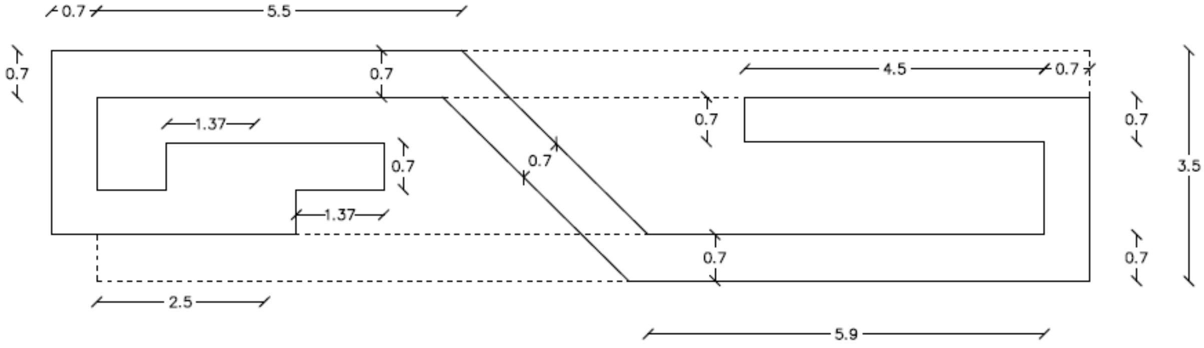


Fig – 8 Interlock tube profile design – 1

4.6.2 Interlock tube profile design – 2

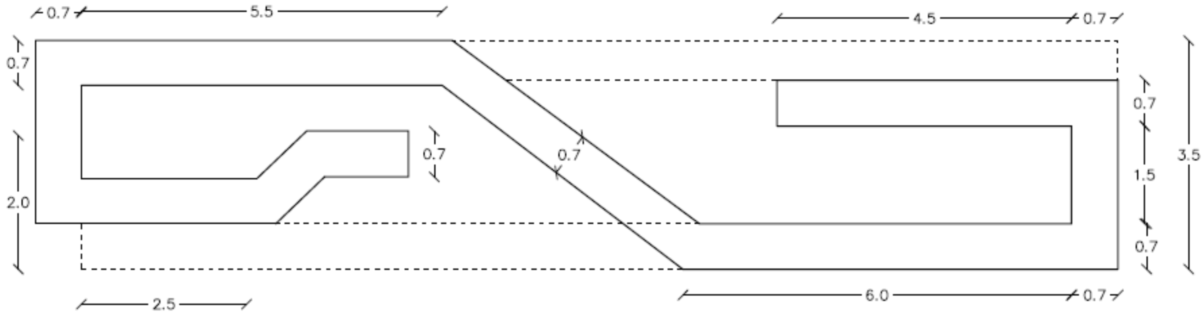


Fig – 9 Interlock profile design – 2

4.6.3 Interlock tube design – 3

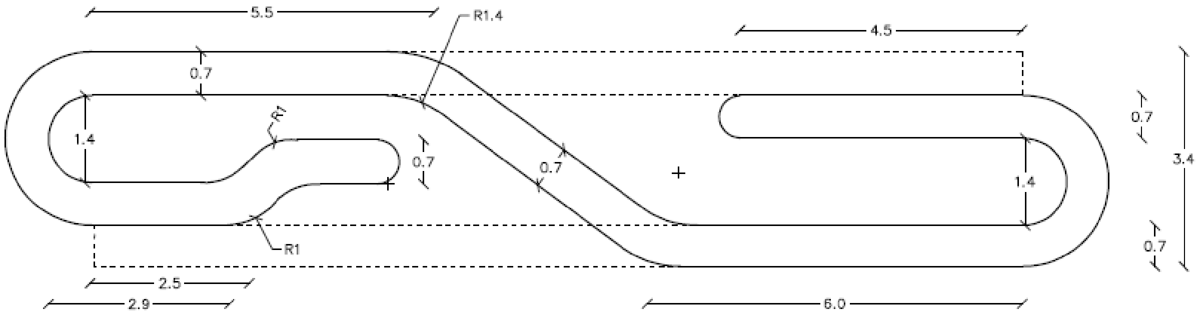


Fig – 10 Interlock profile design – 3

4.6.4 Corrugated pipe design

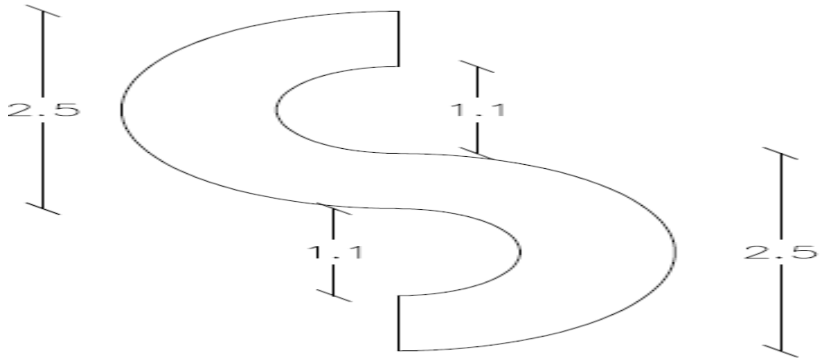


Fig – 11 Corrugated metal pipe

4.7 Material study In this report an overview of failure modes were already seen above. The reason for failure of pipeline is not only design but also selection of material. Long term durability and reliability of flexible pipe is questioned. Recommendations are given for improved robustness and reliability of materials for flexible risers. The carcass is made up of stainless steel that needs to be compatible with chemical constituents of the transported liquids.

The guidance and requirement for material selection should be as follows:

- Material selection evaluations
- Life cycle cost evaluations
- Appropriate specific material selection.
- Design limitation for candidate material
- Qualification guidance new materials or new applications.

Much attention should be given for cost effective and safe use of material which may lead to the introduction of new alloyed materials with good fracture and fatigue resistance. For bulk applications such as flexible pipelines are most likely development would be use of more corrosion resistant materials, improved corrosion control, and gradually increased strength especially for steels.

By stimulating this cross disciplinary interaction, the challenges in material study are related to robust and cost effective solutions. Robust material selection means increased utilization of materials, more narrow tolerances on properties and dimensions and reduced time schedules.

In our case, three different materials which are various grades of steels are used for static analysis named as AISI 304, AISI 316 (SS) and Alloy steel (SS). The choice of materials shall be taken into account for the material property verifying consistency between design requirements.

4.8 Purpose of introducing Alloy grades of stainless steel Flexible pipes are also used in situations where their installations is more cost effective than rigid pipe or where recovery for reuse is necessary. Light weight pipes may also be valuable as static flowline deployed in arctic environment. In order to reduce the weight the replacement of standard steel from heavy grades to alloy grades with light weight and high strength is mandatory.

4.9 Alloy steel grades Common for all stainless steels is a minimum content of 11% Chromium. S13Cr steels have typically 11-12% Chromium. The microstructure is austenite at temperatures beyond 900°C. Rapid cooling suppresses the formation of ferrite and martensite is mainly formed. With higher contents of Chromium than 12%, Nickel (and/or Manganese) must be added to be able to form martensite. Some remaining austenite and ferrite is typically present after cooling. The amount of remaining austenite is part of controlling the strength of S13Cr line pipe materials. Increased amount of remaining austenite reduces the strength. For the low strength S13Cr steels (yield strengths between 500 and 600MPa) it is assumed approximately 15-25% remaining austenite. Increased alloying with Molybdenum increases the corrosion resistance. The low content of carbon is the main contributor for the weldability.

Super martensitic stainless steels are normally divided into three types:
1. Lean grade, 11Cr2Ni
2. Medium grade, 12Cr4.5Ni1.5Mo
3. High alloyed grade, 12Cr6Ni2.5Mo

In the development of this steel type, several alloy sequences have been designed to meet requirements to an increased stress corrosion cracking resistance. In order to meet toughness specifications the ferrite content should be minimized. Hence, the ferrite forming elements such as Cr, Mo and Si must be counterbalanced by austenite stabilistator. In practice, this means Ni since both C and N levels should be lowest possible to maintain the optimum weldability through reduction of hardness.

Strip steel: Ultimate tensile strength, which means the strength at which the steel breaks. For design purpose, yield strength is needed. 0.2% offset strength is common yield strength but has some variability. Instead API 17J uses more consecutive structural strength that is similar to yield strength but is not necessary determined using some test method. API 17J indicates the typical factor is appropriate for extensively cold worked steel and low alloy steel is used in standard flex steel pipes. API 17J specifies the maximum allowable material utilization, essentially reciprocal of design factor. Maximum stress fraction is maximum allowed ratio between actual stress and Ultimate tensile strength.

5. Experimental analysis

To verify carcass layer of flexible steel pipe is suitable for a potential application, a series of worst load cases are defined and analysed to verify that these load cases do not exceed the maximum allowable utilization of the pipe structural members. The Dassault system's Solid work software is used for analysis which accepts pipe geometry and material properties data then calculates the stresses and strains in each layer of the pipe for each load case defined. It determines stresses and strains in carcass layer's interlock profiles under user-defined load conditions, which can include complex combined load cases.

In our case, Statistical analysis is used to determine the relation between pressure and time at a given temperature. The statistical analysis is done in two methods as follows:
Method 1 is more general, is intended for determining the characteristics of new materials, and requires different design of 3 or more. Method 2 is a simplified method intended for variants of existing materials that have already been characterized using method. Outputs these in a tabular format, and compares the resulting stresses and strains to the maximum allowable values. Some properties of interest, such factor of safety and elongation are also reported.

The property of material were experimentally characterised at varying temperature, pressure and loadings. An analytical technique was handled such as bending test and deformation tests in the laboratories. Both tests were uncomplicated and efficient, thus this technique effectively simplifies and describes the material characterisation. Characterization includes fatigue of material also mechanical performance of material is studied. The bending test and deformation test were performed in the laboratory using specimens of interlock tubes and metal corrugated pipe.

5.1 Mechanical description Physical behaviour of carcass layer under loads depends on cross section properties. In order to simplify the problem, we assume radial loads and bending. For flexible pipe, the carcass layer carry most of the radial loads.

5.2 Static analysis – Load case, Results & Analyses Three typical load (Temperature, Internal Pressure and External Pressure) were applied on the model to demonstrate the accuracy and reliability of method. The one end of carcass pipe was constrained and the other end was totally free. Loading is constant along the length of the pipe. The simplified model has the boundary condition is that the one side of tube is fixed. The results of analysis is given below in the tabular column, graph charts also can be referred from appendices A – 1 to A – 4.5.

Table -1: Results of interlock profiles with steel grades applications in static analysis

	CP	**IT Des - 1**	**IT Des – 2**	**IT Des - 3**
AISI 304 (OP)	Yield strength (MPa): 206.8 Deformation scale: 136.797	Yield strength (MPa): 206.8 Deformation scale: 18.812	Yield strength (MPa): 206.8 Deformation scale: 19.82	Yield strength (MPa): 206.8 Displacement(mm) 1.044

	Displacement (mm): 0.04593 Strain: 0.001478 to 0.00006205 FOS: 0.46	Displacement (mm):0.8542 Strain: 0.01557 to 0.000003209 FOS: 0.043	Displacement (mm): 0.8072 Strain: 0.000001490 to 0.01081 FOS: 0.056	Strain: 0.01323 to 0.000003324 Deformation: 15.446 FOS: 0.053
AISI 304 (IP)	Yield strength (MPa): 206.8 Deformation scale: 132.466 Displacement (mm):0.04719 Strain: 0.001575 To 0.00008398 FOS: 0.48	Yield strength (MPa): 206.8 Deformation scale: 21.7359 Displacement (mm): 0.7360 Strain: 0.00001801 to 0.009059 FOS: 0.061	Yield strength (MPa): 206.8 Deformation scale: 20.7393 Displacement (mm): 0.7713 Strain: 0.01014 to 0.00004367 FOS: 0.006	Yield strength (MPa): 206.8 Deformation scale: 11.5811 Displacement(mm) : 1.044 Strain: 0.01323 to 0.000003324 FOS: 0.053
AISI 316 (SS)	Yield strength (MPa): 172.4 Deformation scale: 134.813 Displacement (mm): 0.04588 Strain: 0.001524 to 0.00007399 FOS: 0.39	Yield strength (MPa): 172.4 Deformation scale: 20.123 Displacement (mm):0.7953 Strain: 0.00001537to 0.009692 FOS: 0.047	Yield strength (MPa): 172.4 Deformation scale: 32.7615 Displacement (mm):0.4913 Strain: 0.005192 to 0.00004238 FOS: 0.13	Yield strength (MPa): 172.4 Deformation scale: 565.052 Displacement (mm): 0.03530 Strain: 0.0000000002688 to 0.001029 FOS: 0.57
Alloy steel	Yield strength (MPa): 620.4 Deformation scale: 147.055 Displacement (mm):0.04235 Strain: 0.001403 to 0.00007306 FOS: 1.4	Yield strength (MPa): 620.4 Deformation scale: 21.8886 Displacement (mm): 0.7311 Strain: 0.00001243 to 0.008867 FOS: 0.17	Yield strength (MPa): 620.4 Deformation scale: 35.7401 Displacement (mm): 0.4504 Strain: 0.00001654 to 0.004779 FOS: 0.46	Yield strength (MPa): 620.4 Deformation scale: 255.981 Displacement (mm): 0.06520 Strain: 0.0000001490 to 0.001000 FOS: 1.7

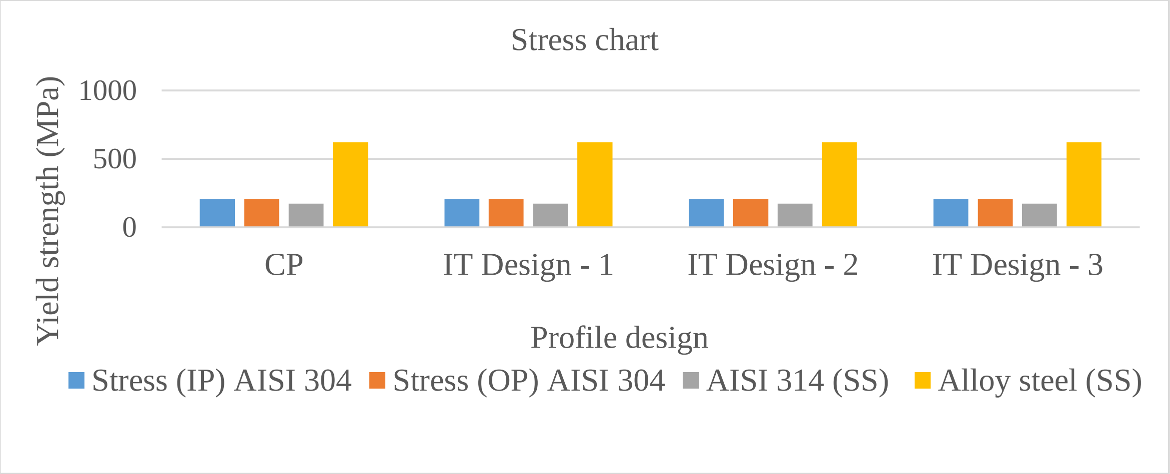


Fig – 12 Stress chart

The stress chart shows the alloy steel commonly in all the design profiles gives good yield strength.

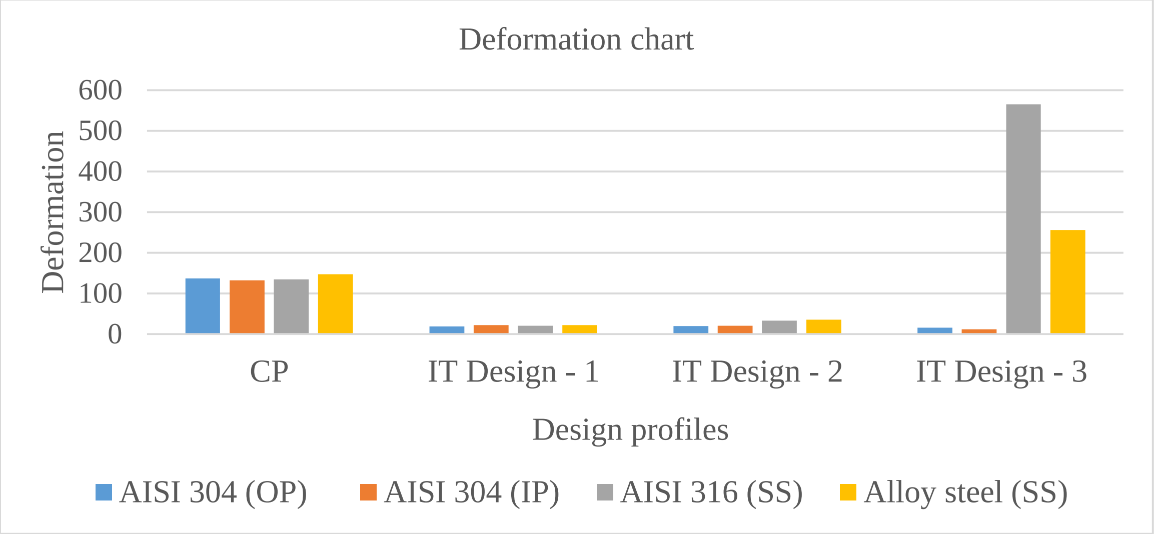


Fig – 13 Deformation chart

The deformation scale chart shows the corrugated pipe undergoes similar deformations whereas the deformation of interlocked pipe shows huge variation irrespective of material and design.

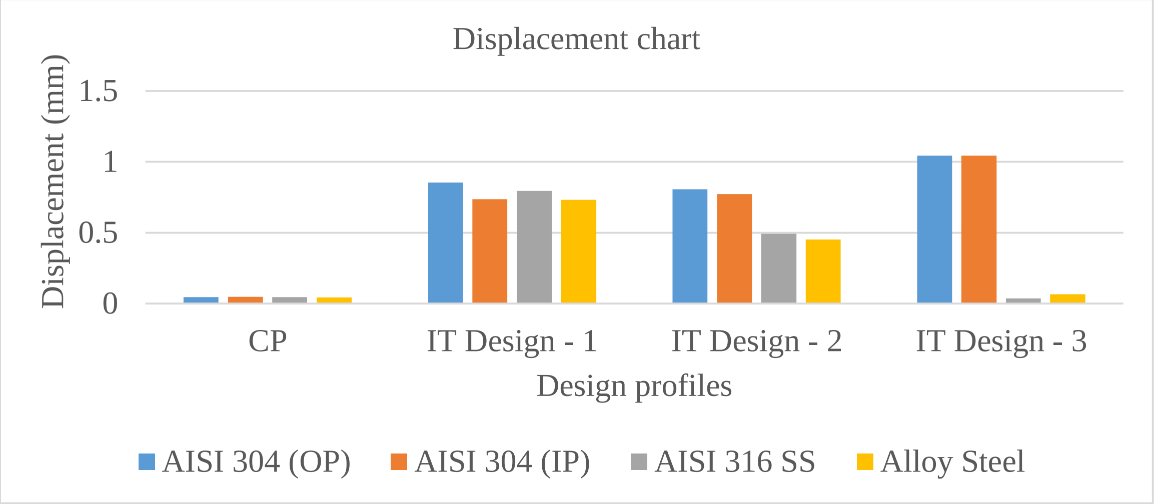


Fig – 14 Displacement chart

The displacement chart shows that corrugated pipe has similar values of displacement results without much difference like deformation scale and the design profile – 3 shows highest displacement with AISI 304 (pressure acting either internally or externally.) and the AISI 316 SS and alloy steel records the lowest displacement.

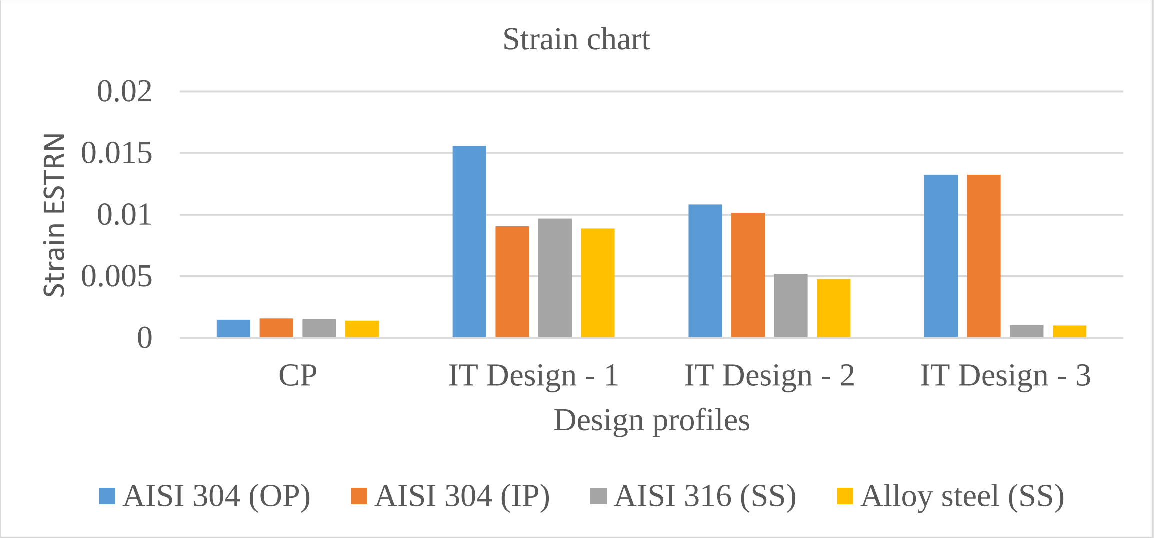


Fig – 15 Strain chart

The strain chart also shows that corrugated pipe has similar values of strain results without much difference like deformation scale and the design profile – 3 shows highest displacement with AISI 304 (pressure acting either internally or externally.) and the alloy steel records the lowest strain.

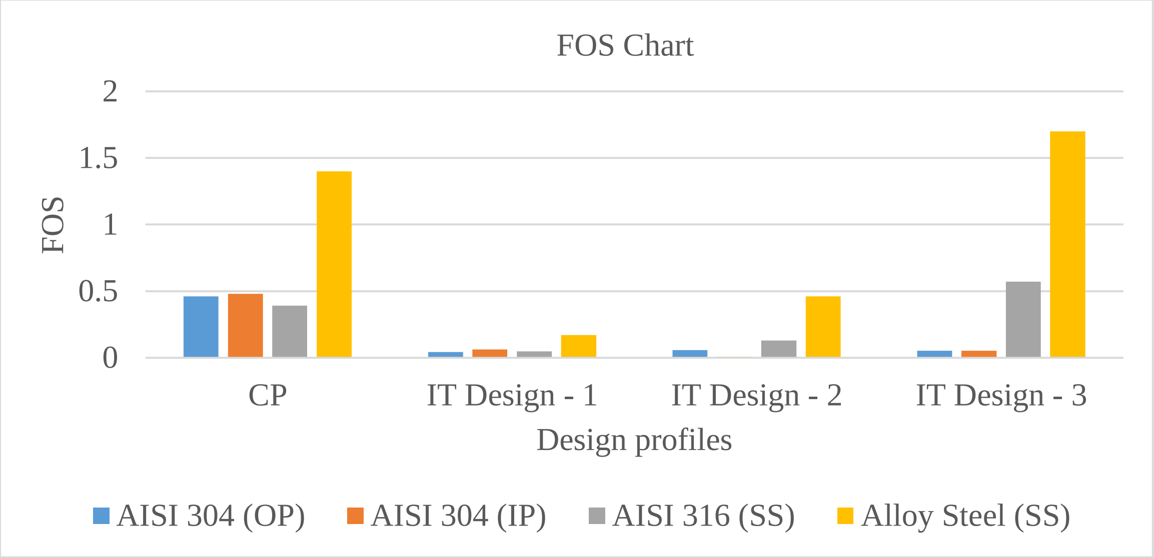


Fig – 16 FOS chart

The FOS chart also shows the alloy steel material gives the highest FOS for both design profile as well as corrugated pipe.

5.3 Lab experiments over Interlock tube:

Fig – 17 Deformation testing at laboratory

5.3.1 Deformation test of Interlock tube: Test – 1

Mat: Galvanised steel **OD:** 26 mm **ID:** 21.5mm
Strip size:
Thickness: 0.3 mm **Area of cross section:** 3 mm

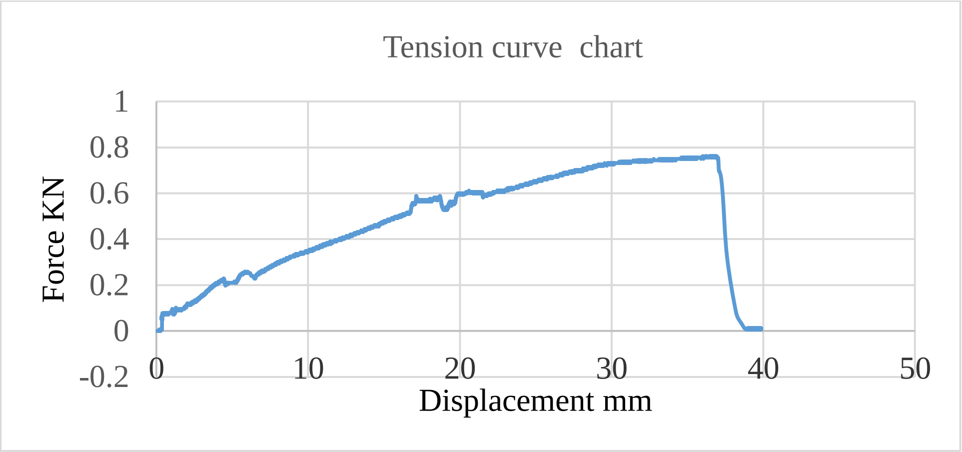


Fig – 18 Tension curve chart– test 1

The maximum displacement undergone by this pipe is 39.87 mm and average displacement is 19.44mm

5.3.2 Test – 2

Mat: Galvanised steel **OD:** 26 mm **ID:** 21.5mm
Strip size:
Thickness: 0.3 mm **Area of cross section:** 3 mm

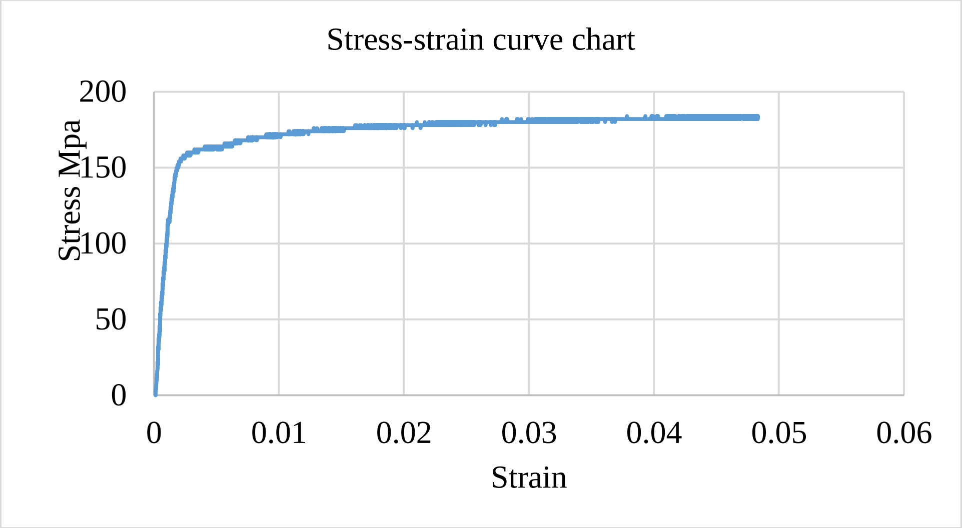


Fig – 19 Stress strain curve chart– test 2

The max stress undergone by this pipe is 186 MPa and average is 93MPa which is similar to the results with materials like AISI 304 and AISI 316 SS. The maximum strain is 0.0001248 mm. Thereby proving that the simulation results shows similarity in agreeing with the laboratory results proving the interlock tubes has same structural behaviours.

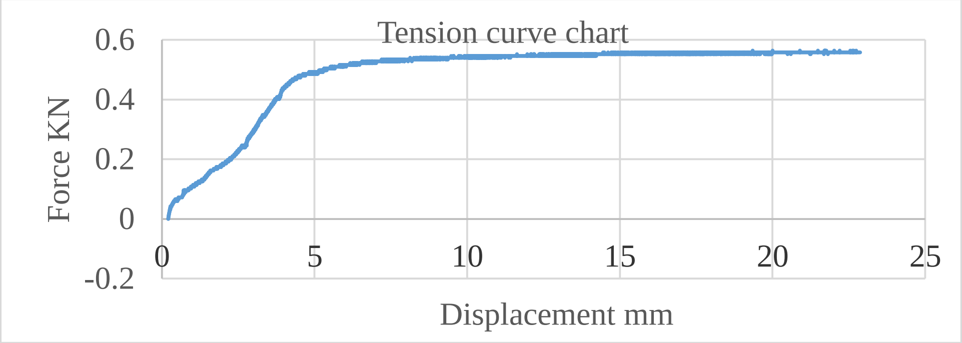


Fig – 20 Tension curve chart – test 2

The average displacement recorded is 11.53mm and maximum displacement is 22.87 mm

5.3.3 Test – 3

Mat: Galvanised steel **OD:** 26 mm **ID:** 21.5mm

Strip size:

Thickness: 0.3 mm **Area of cross section:** 3 mm

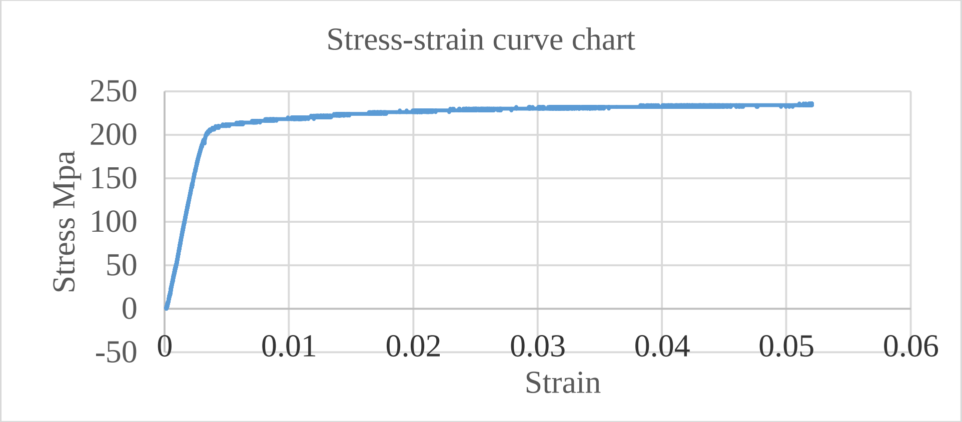


Fig – 21 Stress strain curve chart– test 3

The max stress undergone is 236MPa and average is 167.0443. The average strain is max is 0.052056.

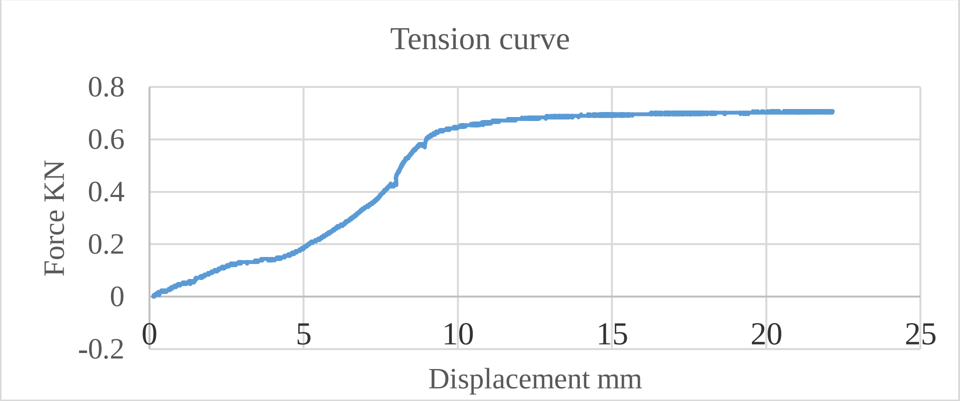


Fig – 22 Tension curve – test 3

The relationship of stress and strain curve. The relationship between force and displacement, stress and strain are plotted in graph for interlocked tubes and force and bending diagram is also given for corrugated pipe. The results presented here are in average slope which exhibits effectively linear behaviour as expected.

5.4 Observations

5.4.1. Observation from design analysis

Appendices from A-1 to 4.5 shows the deformations visually good. Especially corrugated pipe design gives similar static analysis results irrespective of different materials used; whereas the interlock tubes show huge variations in results. But the interlock tube design - 3 records highest FOS which can be considered as better design comparatively than the other two design profiles. Interlock tube design – 3 is the current standard design of carcass layer manufactured in the industries and used in offshore lines. The main design problem of the carcass is to provide the structural strength against external loads. This problem is related to material grade through material strength properties and formability of fabrication.

5.4.2 Observation from material property of carcass: Stainless steel

Stainless steel is used for the carcass structure. Standard grades are generally used, 304, 316 and similar. No problems related to material properties (corrosion, fatigue, wear, etc.) have been reported in the open literature. The failure is linked with design input, design and material knowledge. The failure modes and corresponding design criteria are related to complicated time-dependent material performance, like creep, thermal cycling and ageing, and to the interaction between the thermoplastic liner and metallic components, that cannot be modelled properly which is studied deeply below under topic deformation of carcass. The alloy steel expresses better material property comparative to other grades of steel.

Tab – 2: Material property of steel grades undergone static analysis

Carcass Layer	**AISI 304**	**AISI 316 SS**	**Alloy steel**
Density (kg/m^3)	8000	8000	7700
Young's modulus (N/m^2)	1.90e$^{+0.11}$	1.92e$^{+0.11}$	2.10 e^{+011}
Poisson's ratio	0.29	0.27	0.28
Tensile strength (N/m$^{2)}$	517017000	580000000.8	723825617
Yield strength (N/m^2)	206807000	172368932.3	620421997.8

Agreement obtained from numerical and mechanical analytical comparisons validates use of numerical results here. The results shows that the numerical model takes into account of various details of flexible pipe. It has been shown that the detailed model can be used to predict the mechanical behaviour under various load cases and bound conditions such as the position of entire pipeline is obtained under the assumption that pipeline is lying on the sea bed, which means external pressure is 10Mpa. In this case the conditions applied shows the radial deformation. The maximum stretch of carcass layer over different designs and material applications gives the values of deformation, displacement, stress and strain in the below tabular column.

5.5 Deformation of carcass From the above static analysis, it is seen that the carcass layer undergoes critical deformations. The evaluations in the critical sections of the interlock tube as it responds to the overall pipe loading configurations. After a very large accumulated number of load cycles under conditions of severe strain, these interlock tubes undergo fatigue cracking which is the first physical sign of damage in the entire pipe. The picture of deformation can be seen from the static analysis simulations. (Refer appendix.)

5.6 Numerical studies One of the main purposes of this chapter is to study how the numerical solution can be influenced by different parameters. In addition the numerical and analytical solutions are compared for both loading and bending. The aim of the comparisons is to verify the numerical model can give adequate description of structural strength of interlock tube and metal corrugated pipe. On the other hand it can also be used to prove that the developed numerical model can give adequate description over deformation of interlock profile.

Also an investigation on the bending test of corrugated pipe and bending behaviour of carcass is studied. This is done to find out the possibility of adapting the corrugated pipe design for the inner most layer of flexible pipe replacing carcass structure. Also finally the influence from deformation of corrugated pipe and interlock tube is studied below.

5.7 Loading and deformation mechanisms From the literature analysis and static analysis, we could see the design of interlock tubes experiences the radial outwards loading created by the factors like pressure and temperature. However a detailed analysis has done and results that the interlock tube can be axially stressed while pipe is under tension or bending. The gap between the adjacent turns of interlock is responsible for the flexibility of the tube and the size of the gap is also the major factor in determining the minimum bend radius of the pipe. The adjacent turns are intended to slide with respect to each other thus avoiding axial loading of the tube resulting from pipe tension or bending. The key feature of the model is that they treat the radial deformations as unknown variables to be determined based on the geometry and material of carcass layer.

When a pipe is under tension, the adjacent turns of the interlock will slide relative to each other which results in following actions such as development of loads like radial and intrusion pressure, interface reaction forces and interface friction forces. Assuming the pipe is bent, the gaps between the adjacent turns of interlock on one side will tend to open and those of convex slide to shut. The loading mechanism of interlock on one side will be different from the other side. The purpose of the work is to identify consider sufficient loading system acting on the concave side of the tube. The some differences exist between two main cases. This is due to the fact in bending case not only adjacent turns slide but also they will rotate adjacent side to each other which results in shift of points of action of the interface reaction forces. The positions of these points of action will depend on the clearances between adjacent turns and relative rigidities of different parts of the turn.

5.7.1 Difference between inward and outward radial force

Fig – 23 Radial pressure acting from inside

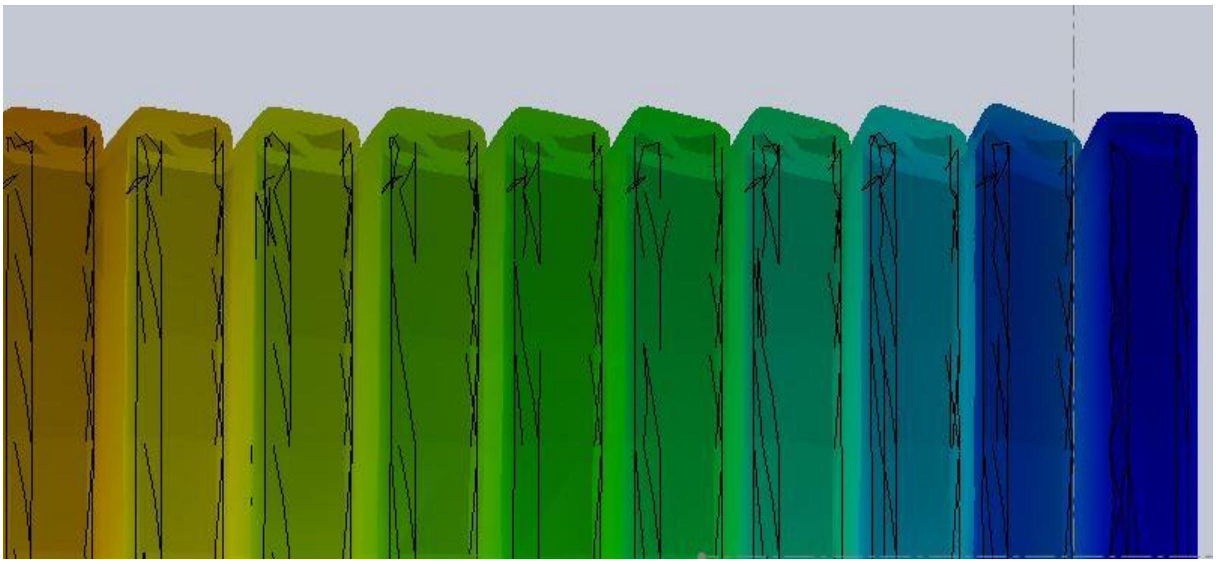


Fig – 24 Radial pressure acting from outside

5.8 Experiment of bending test over Metal corrugated pipe well known materials are used in "new" applications or "new" materials are to be used, the qualification may be by reference to results from relevant laboratory or production tests. Also in order to characterize the material under study, a wide range of conducting experiments are mandatory. This is termed as “Qualification by general test data.”

In our case we experimented the specimens with the tests like deformation and bending curve test to check out the adaptation possibility of metal corrugated pipe, the bend test was one of the method to find out strength of pipe.

A metal corrugated pipe specimen of 200mm length was used. The aim of the sub – chapter is to study the specimen’s bending behaviour. Comparison between analytical and numerical results with the help of model described. Two specimens are used to produce comparative result and the below pictures show that the pipe is bent step by step in the bending test machine.

Pic of specimen

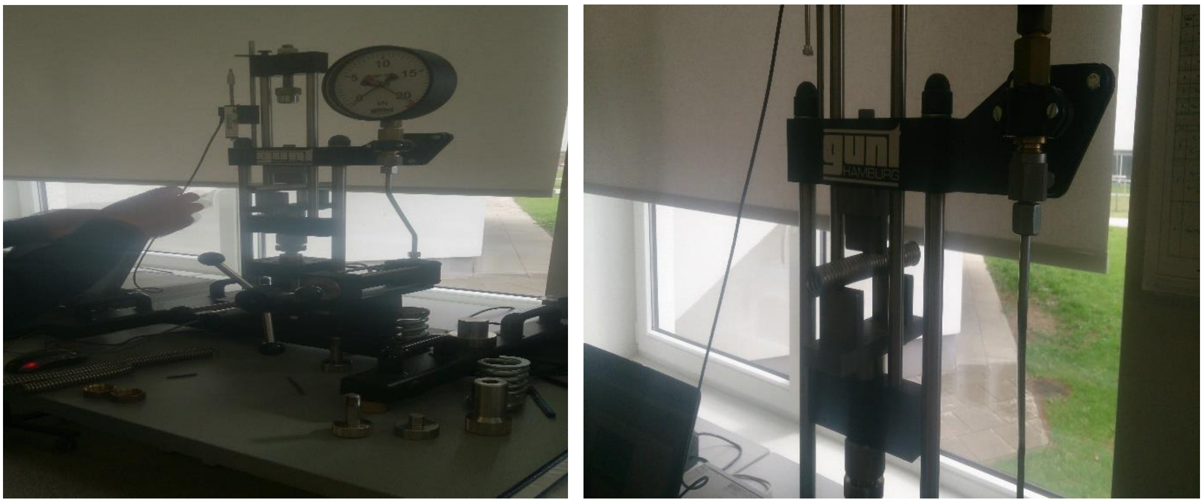
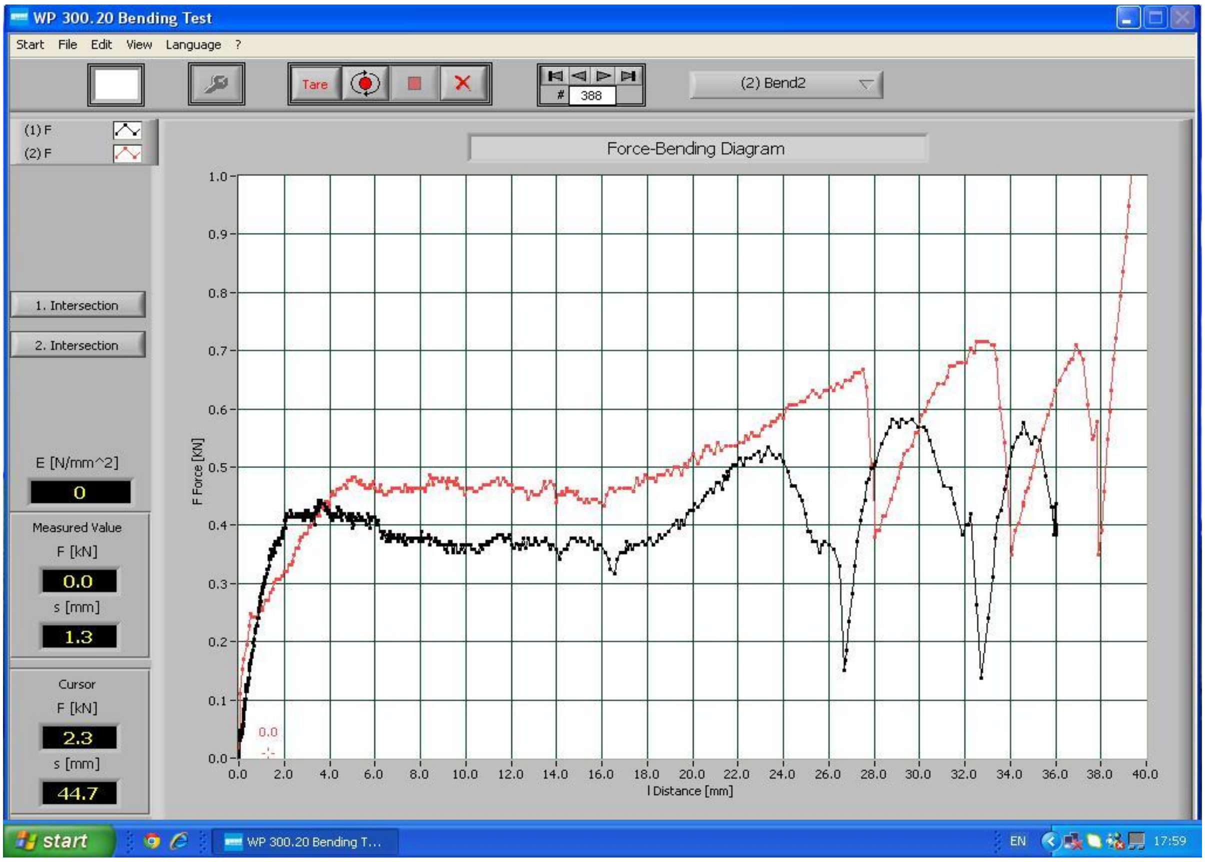


Fig – 30 Bending Machine

Test details:
Test Name: Bend1
Code: WP 300.20
Date: 19.02.2015 Time: 18:00:16



388

(2) Bend2

E [N/mm^2] 0

Measured Value
F [kN] 0.0
s [mm] 1.3

Cursor
F [kN] 2.3
s [mm] 44.7

Fig – 31 Force – Bending Diagram

The experimental part of bending behaviour gives the numerical solution and laboratory test results reasons for the adaptation of carcass layer in the flexible pipe instead of corrugated pipe. The carcass layer shows better results in terms of displacement than metal corrugated pipe and the flexibility of carcass is higher than corrugated metal pipes. Hence this proves interlock carcass layer are better suitable ones than metal corrugated pipe.

6. Conclusions and recommendations

The static application under deep sea uses flexible pipelines. It is difficult for installation of rigid and weight pipelines also highly expensive for installations and recovery of reuse. So flexible pipes are a better alternative for rigid pipes.

The results of this case study has suitable model for predicting the structural response of carcass layer. The design of carcass layer is well understood as a result of extensive testing and analysis to verify and calibrate the design methodology. The design of carcass is largely covered by API document through some design variations from the classic products around which the API documents were developed do exist. This is extremely encouraging when one considers the complexity of these flexible structures. However, design basis for the flexible pipelines are insufficient since most analysis are run based on assumptions

The maximum value of strain of deformation test – 2 is 0.0001248 and test – 3 is 0.052056 is nearby value of static analysis results of Design – 3 with material application of Alloy steel is 0.01323 and 0.001000 shows that this design and material property combination can withstand highest possibility of strain.

The elongation on turns is visually observed from static analysis. The literature survey says that the strains on the critical area of interlock corresponds to the elongation of the turn is seen in the strain results. Refer appendix A – 1 to A – 4.5 for pictures. The stress value of deformation test – 2 and 3 are 236 and 186 MPa which has difference from static analysis results. The static analysis results shows 206.8and 172.4 MPa. This variations is due to the material property and weight of materials. The literature survey says different grades of steel exposes different material and mechanical behaviour. Much attention should be given for new alloys of material with good fracture, fatigue resistance also with low weight and high strength.

Flexibility obtained by the ability of each profile to slide with respective to the neighbouring profiles. But whereas when it comes to the corrugated pipes the flexibility is very limited due to its design structure which shows poor displacement of 0.4593 mm in average irrespective of various material applications. The maximum displacement given by interlock tube in design – 3 from static analysis is 1.044 mm and lab results are 11 mm in average whereas the corrugated pipe shows poor result of 0.04mm which is comparatively less shows limited flexible nature. In case of application of sudden force or more design or operational pressure over this pipes will result in crack of pipe easily.

The factor radial gap plays a vital role in collapse of carcass. The interlock strips can undergo stretches and elongation. As per the literature survey, it is very hard to calculate radial gaps. But the elongation and stretch of interlock tube is very high along with its flexibility nature compared to the corrugated pipes. The plasticity property of material adds extra value to the carcass layer. But the corrugated pipe’s radial gaps i.e. the distance between the two pitches are very short even though it is measurable. The structure and shape of corrugated pipe shows poor flexibility change in the sizes of pitch may result in complete change of Inner diameter of pipes.

The overall conclusion is that the developed model is capable of describing stresses and local displacement of carcass for simple cases. It can further be used for the study of fatigue of carcass. The possibility of adaptation of corrugated metal pipes in flexible oil pipeline can be made a test run limiting to the case of static analysis since it can withstand good stress concentrations and larger moment of inertia offer great stiffness like carcass. As per the literature survey, the common similarity for both flexible pipe and corrugated pipe is deflection which is the most important performance limit. Therefore the corrugated pipes can be recommended to use in the limited case of proper buried pipelines or clamping with structurals which prevents the movement of pipe due to tides and waves since the corrugated metal pipes show average results of stretch, elongation and displacements when compared to interlock tubes. The above results are based upon the value analysis and engineering methodology which is the application of exactly the same techniques to an existing product at design stage with a view to improve its value.

7. Reference List

1. AC02892301, A. *Advances in Underwater Technology, Ocean Science and Offshore Engineering.* Graham & Trotman, 1986.

2. ALFANO, G., BAHTUI, A. and BAHAI, H. Numerical Derivation of Constitutive Models for Unbonded Flexible Risers. *International Journal of Mechanical Sciences*, 2009, vol. 51, no. 4. pp. 295-304.

3. BAI, Q. and BAI, Y. *Subsea Pipeline Design, Analysis, and Installation.* Gulf Professional Publishing, 2014.

4. BAI, Y. and BAI, Q. *Subsea Pipelines and Risers.* Elsevier, 2005.

5. CHEN, M. Fatigue Analysis of Flexible Pipes using Alternative Element Types and Bend Stiffener Data, 2011.

6. CHEN, M. Fatigue Analysis of Flexible Pipes using Alternative Element Types and Bend Stiffener Data, 2011.

7. CHEN, Z., REUBEN, R. and OWEN, D. The Deformation Mechanics of Interlock Tubes. *Strain*, 1992, vol. 28, no. 3. pp. 99-106.

8. CLARKE, T., et al. Monitoring the Structural Integrity of a Flexible Riser during a Full-Scale Fatigue Test. *Engineering Structures*, 2011, vol. 33, no. 4. pp. 1181-1186.

10. CUAMATZI-MELENDEZ, R., et al. Finite Element Modeling of Burst Failure in Unbonded Flexible Risers. *Engineering Structures*, 2015, vol. 87. pp. 58-69.

11. CZERWIŃSKI, A. and ŁUCZKO, J. Vibrations of Steel Pipes and Flexible Hoses Induced by Periodically Variable Fluid Flow. *Mechanics and Control*, 2012, vol. 31. pp. 63-71.

12. FERET, J. and BOURNAZEL, C. Calculation of Stresses and Slip in Structural Layers of Unbonded Flexible Pipes. *Journal of Offshore Mechanics and Arctic Engineering*, 1987, vol. 109, no. 3. pp. 263-269.

13. FRANZINI, G.R., et al. *Crushing of Flexible Pipes Under Traction: A Theoretical-Experimental Assessment.* American Society of Mechanical Engineers, 2011.

14. GONG, S., LAM, K. and LU, C. Structural Analysis of a Submarine Pipeline Subjected to Underwater Shock. *International Journal of Pressure Vessels and Piping*, 2000, vol. 77, no. 7. pp. 417-423.

15. GRYTÅ, G. Fatigue of Flexible Riser in Bend Stiffner Area, 2011.

16. KALLIONTZIS, C., ANDRIANIS, E., SPYROPOULOS, K. and DOIKAS, S. Nonlinear Static Stress Analysis of Submarine High Pressure Pipelines. *Computers & Structures*, 1997, vol. 63, no. 3. pp. 397-411.

17. KALLIONTZIS, C., ANDRIANIS, E., SPYROPOULOS, K. and DOIKAS, S. Nonlinear Static Stress Analysis of Submarine High Pressure Pipelines. *Computers & Structures*, 1997, vol. 63, no. 3. pp. 397-411.

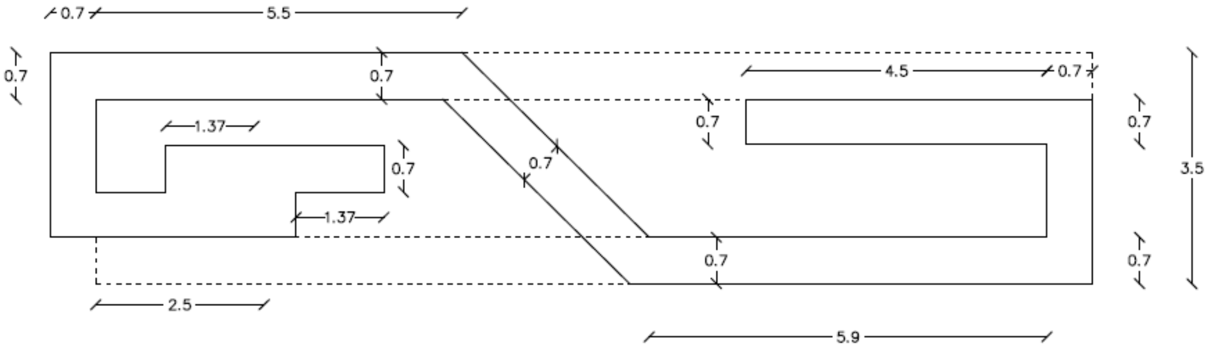
18. KIM, M.K., CHO, S.H., YUN, I.J. and WON, J.H. Three-dimensional Responses of Buried Corrugated Pipes and ANN-based Method for Predicting Pipe Deflections. *International Journal for Numerical and Analytical Methods in Geomechanics*, 2012, vol. 36, no. 1. pp. 1-16.

19. LEFFLER WILLIAM, L., RICHARD, P. and GORDON, S. Deepwater Petroleum Exploration and Production. *Tulsa, OK: PennWell Corporation*, 2011.

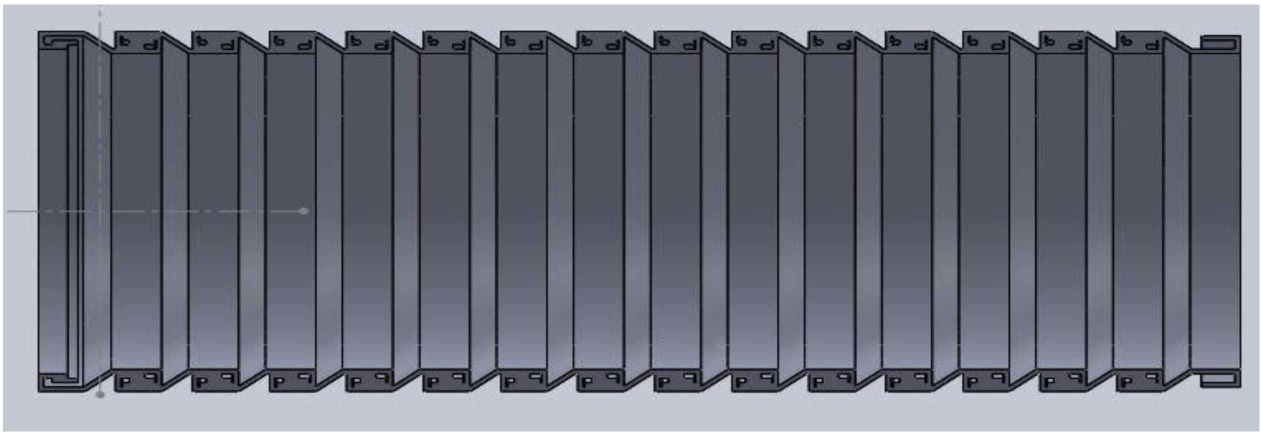
20. LI, H. Flexible Pipe Stress and Fatigue Analysis, 2012.
21. LI, J., QIU, Z. and JU, J. Numerical Modeling and Mechanical Analysis of Flexible Risers.
22. LIU, R., XIONG, H., WU, X. and YAN, S. Numerical Studies on Global Buckling of Subsea Pipelines. *Ocean Engineering*, 2014, vol. 78. pp. 62-72.
23. LOVERICH, J.S. *Life Prediction of Composite Armor in an Unbonded Flexible Pipe*, 1997.
24. LU, X. Dynamic Response of Flexible Pipes during Installation, 2013.
25. MCIVER, D. A Method of Modelling the Detailed Component and overall Structural Behaviour of Flexible Pipe Sections. *Engineering Structures*, 1995, vol. 17, no. 4. pp. 254-266.
26. MONPRAPUSSORN, T., CHUCHEEPSAKUL, S. and HUANG, T. The Coupled radial–axial Deformations Analysis of Flexible Pipes Conveying Fluid. *International Journal for Numerical Methods in Engineering*, 2004, vol. 59, no. 11. pp. 1399-1452.
27. ORYNYAK, I. and RADCHENKO, S. Analytical and Numerical Solution for a Elastic Pipe Bend at in-Plane Bending with Consideration for the End Effect. *International Journal of Solids and Structures*, 2007, vol. 44, no. 5. pp. 1488-1510.
28. ØSTERGAARD, N.H., LYCKEGAARD, A. and ANDREASEN, J. Simulation of Frictional Effects in Models for Calculation of the Equilibrium State of Flexible Pipe Armouring Wires in Compression and Bending. *Rakenteiden Mekaniikka (Journal of Structural Mechanics)*, 2011, vol. 44, no. 3. pp. 243-259.
29. ØSTERGAARD, N.H., LYCKEGAARD, A. and ANDREASEN, J.H. A Method for Prediction of the Equilibrium State of a Long and Slender Wire on a Frictionless Toroid Applied for Analysis of Flexible Pipe Structures. *Engineering Structures,* 2012, vol. 34. pp. 391-399.
30. OUT, J. and VON MORGEN, B. Slippage of Helical Reinforcing on a Bent Cylinder. *Engineering Structures*, 1997, vol. 19, no. 6. pp. 507-515.
31. PATEL, M. and SEYED, F. Review of Flexible Riser Modelling and Analysis Techniques. *Engineering Structures*, 1995, vol. 17, no. 4. pp. 293-304.
32. PATEL, M. and SEYED, F. Review of Flexible Riser Modelling and Analysis Techniques. *Engineering Structures*, 1995, vol. 17, no. 4. pp. 293-304.
33. RABELO, M.A., et al. An Investigation on Flexible Pipes Birdcaging Triggering. *Marine Structures*, 2015, vol. 40. pp. 159-182.
34. SAEVIK, S. and BERGE, S. Fatigue Testing and Theoretical Studies of Two 4 in Flexible Pipes. *Engineering Structures*, 1995, vol. 17, no. 4. pp. 276-292.
35. SÆVIK, S. and BRUASETH, S. Theoretical and Experimental Studies of the Axisymmetric Behaviour of Complex Umbilical Cross-Sections. *Applied Ocean Research,* 2005, vol. 27, no. 2. pp. 97-106.
36. SÆVIK, S. Theoretical and Experimental Studies of Stresses in Flexible Pipes. *Computers & Structures*, 2011, vol. 89, no. 23. pp. 2273-2291.
37. SAVENKOV, V. and SOLODOVA, L. State of Stress and Strain of a Multilayered Composite Flexible Pipe Reinforced by Helical Carcass. *Mechanics of Composite Materials*, 1988, vol. 23, no. 6. pp. 762-768.

38. SHEN, Y., RUSSELL, C. and ANDERSON, K. *Investigation of Flexible Pipe Tensile Armour Bending Curvature Equations and Associated Bending Stress.* International Society of Offshore and Polar Engineers, 2014.
39. SIMONSEN, A. Inspection and Monitoring Techniques for Un-Bonded Flexible Risers and Pipelines, 2014.
40. STANDARD, N. Materials Selection, 1994.
41. TANG, M., YANG, C., YAN, J. and YUE, Q. Validity and Limitation of Analytical Models for the Bending Stress of a Helical Wire in Unbonded Flexible Pipes. *Applied Ocean Research*, 2015, vol. 50. pp. 58-68.
42. VAZ, M. and RIZZO, N. A Finite Element Model for Flexible Pipe Armor Wire Instability. *Marine Structures*, 2011, vol. 24, no. 3. pp. 275-291.
43. VEERAPPAN, A. and SHANMUGAM, S. Analysis for Flexibility in the Ovality and Thinning Limits of Pipe Bends. *Ratio*, 2006, vol. 4796, no. 85.20. pp. 85.20.
44. VERITAS, D.N. Structural Analysis of Piping Systems. *Norway: DNV*, 2008.
45. WANG, W. and CHEN, G. Analytical and Numerical Modelling for Flexible Pipes. *China Ocean Engineering*, 2011, vol. 25. pp. 737-746.
46. WIGGERT, D.C. and TIJSSELING, A.S. Fluid Transients and Fluid-Structure Interaction in Flexible Liquid-Filled Piping. *Applied Mechanics Reviews*, 2001, vol. 54, no. 5. pp. 455-481.
47. WITZ, J. A Case Study in the Cross-Section Analysis of Flexible Risers. *Marine Structures*, 1996, vol. 9, no. 9. pp. 885-904.
48. YUE, Q., et al. Tension Behavior Prediction of Flexible Pipelines in Shallow Water. *Ocean Engineering*, 2013, vol. 58. pp. 201-207.
49. Ref: https://www.atimetals.com/markets/oilandgas/Documents/Flexible%20Flowlines.pdf
50. Dr.V.Jayakumar. Production planning and control. Lakshmi publications. Third edition 2011. Pp – 3.9 – 3.10.
51. https://www.atimetals.com/markets/oilandgas/Documents/Flexible%20Flowlines.pdf
52. http://www.ptil.no/getfile.php/z%20Konvertert/Helse,%20milj%C3%B8%20og%20 sikkerhet/Sikkerhet%20og%20arbeidsmilj%C3%B8/Dokumenter/sintef.pdf [02.03.14]
53. Shell projects and technology 16 -12 – 10 – Klvl lecture – How to live with flexible pipe, happily ever after? – J.M.M. (Hans) Out.[03.04.14]

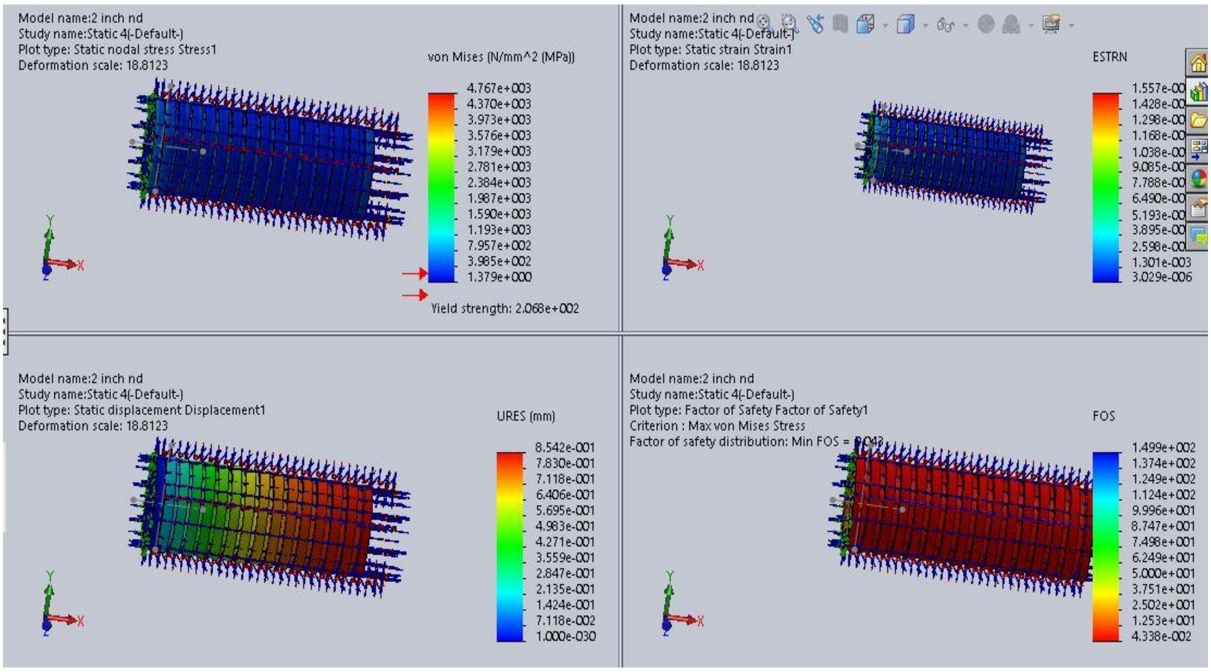
8.Appendix



A – 1 Dimensions of interlock profile design – 1



A- 1.1 Cross section of complete tube design – 1



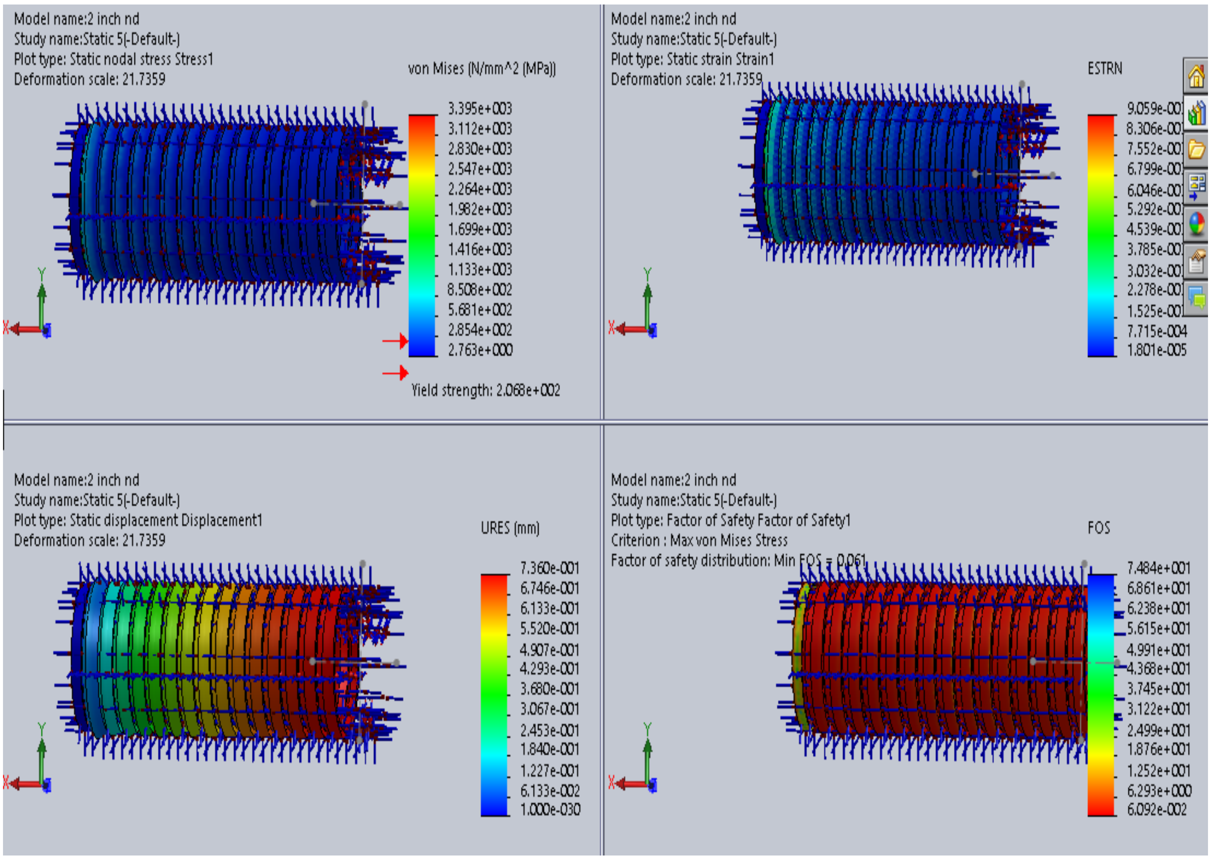
Model name:2 inch nd
Study name:Static 4(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 18.8123

Model name:2 inch nd
Study name:Static 4(-Default-)
Plot type: Static strain Strain1
Deformation scale: 18.8123

Model name:2 inch nd
Study name:Static 4(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 18.8123

Model name:2 inch nd
Study name:Static 4(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Max von Mises Stress
Factor of safety distribution: Min FOS = 0.043

A – 1.2 Compare results of stress, strain displacement and FOS - Pressure acting from outside: Pressure: 10 MPa and Temp: 30°C Mat: AISI 304



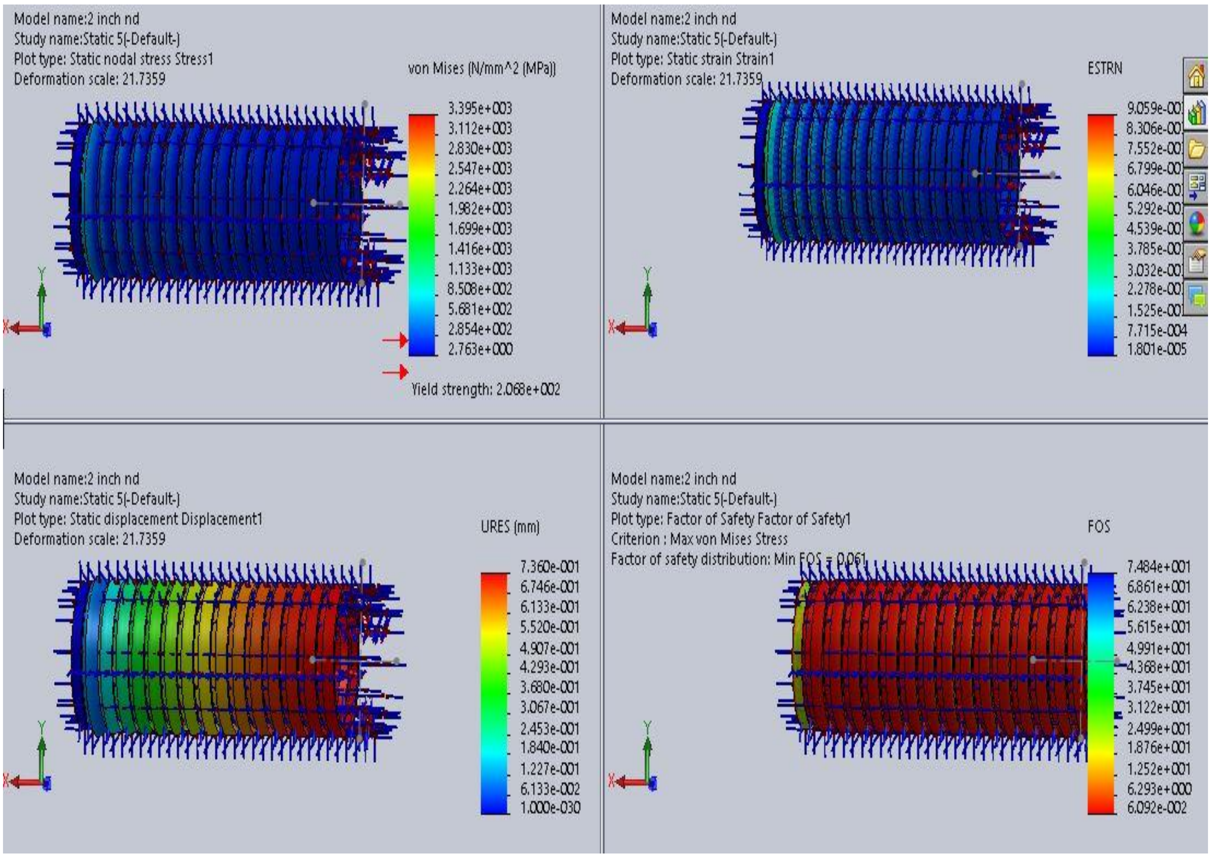
Model name:2 inch nd
Study name:Static 5(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 21.7359

Model name:2 inch nd
Study name:Static 5(-Default-)
Plot type: Static strain Strain1
Deformation scale: 21.7359

Model name:2 inch nd
Study name:Static 5(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 21.7359

Model name:2 inch nd
Study name:Static 5(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Max von Mises Stress
Factor of safety distribution: Min FOS = 0.061

A – 1.3 Pressure acting from inside: Pressure: 10 MPa and Temp: 30°C Mat: AISI 304



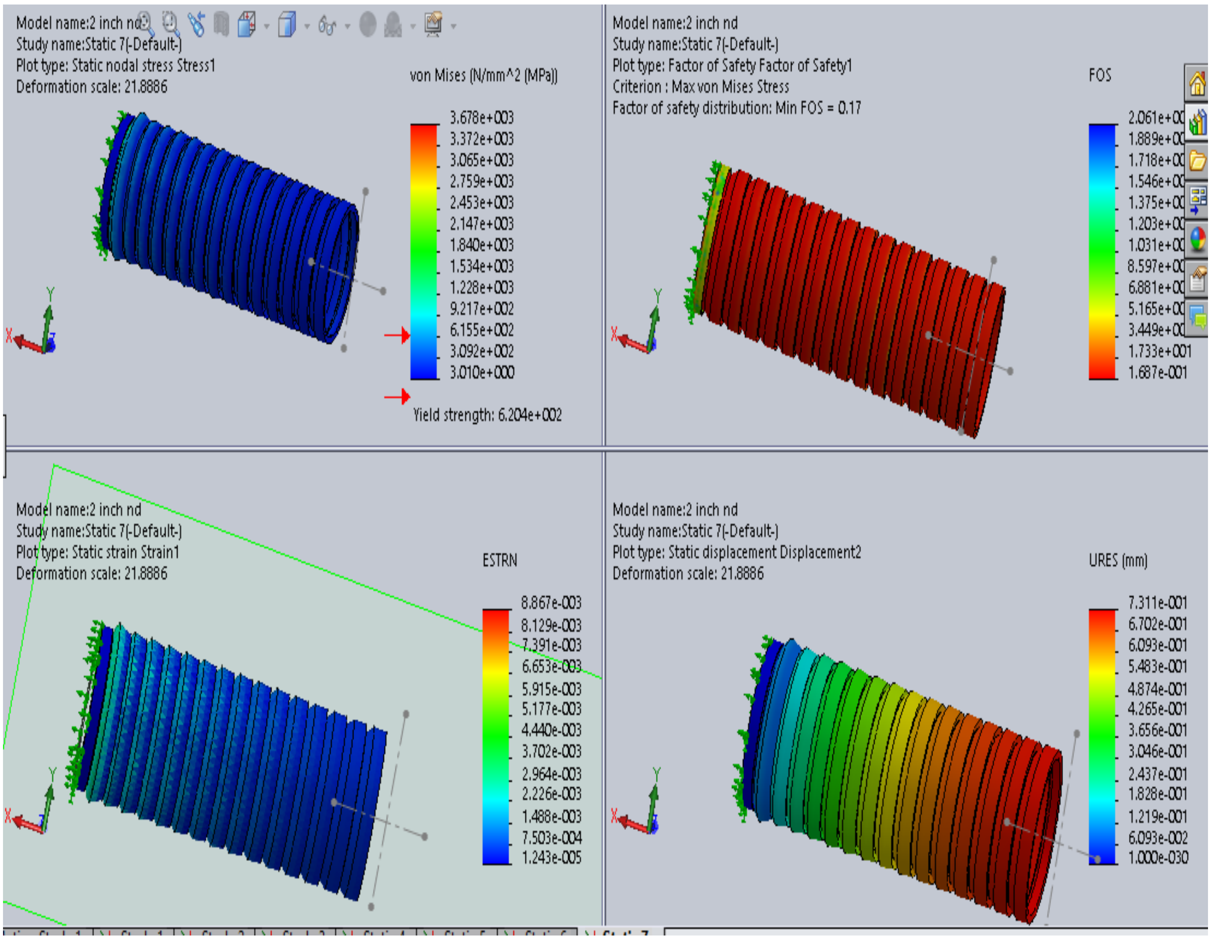
Model name:2 inch nd
Study name:Static 5(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 21.7359

Model name:2 inch nd
Study name:Static 5(-Default-)
Plot type: Static strain Strain1
Deformation scale: 21.7359

Model name:2 inch nd
Study name:Static 5(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 21.7359

Model name:2 inch nd
Study name:Static 5(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Max von Mises Stress
Factor of safety distribution: Min FOS = 0.061

A – 1.4 Pressure: 10 MPa and Temp: 30°C Mat: AISI 316 (SS)



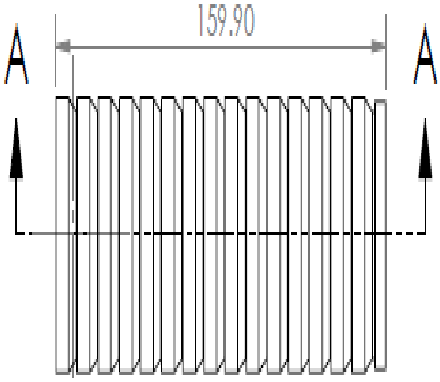
Model name:2 inch nd
Study name:Static 7(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 21.8886

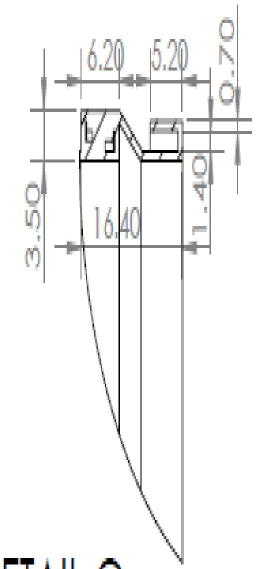
Model name:2 inch nd
Study name:Static 7(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Max von Mises Stress
Factor of safety distribution: Min FOS = 0.17

Model name:2 inch nd
Study name:Static 7(-Default-)
Plot type: Static strain Strain1
Deformation scale: 21.8886

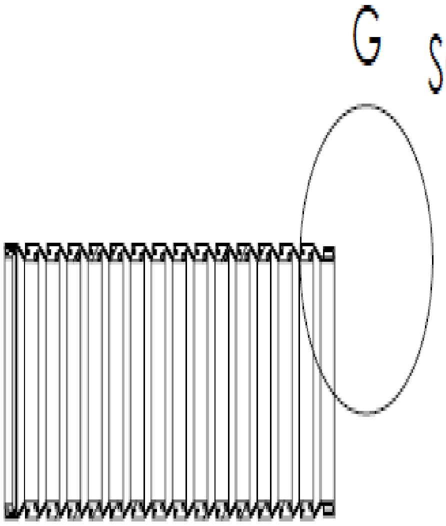
Model name:2 inch nd
Study name:Static 7(-Default-)
Plot type: Static displacement Displacement2
Deformation scale: 21.8886

A – 1.5 Pressure: 10 MPa and Temp: 30°C Mat: Alloy steel (SS)

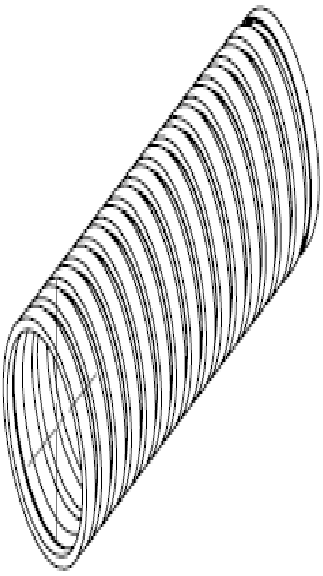




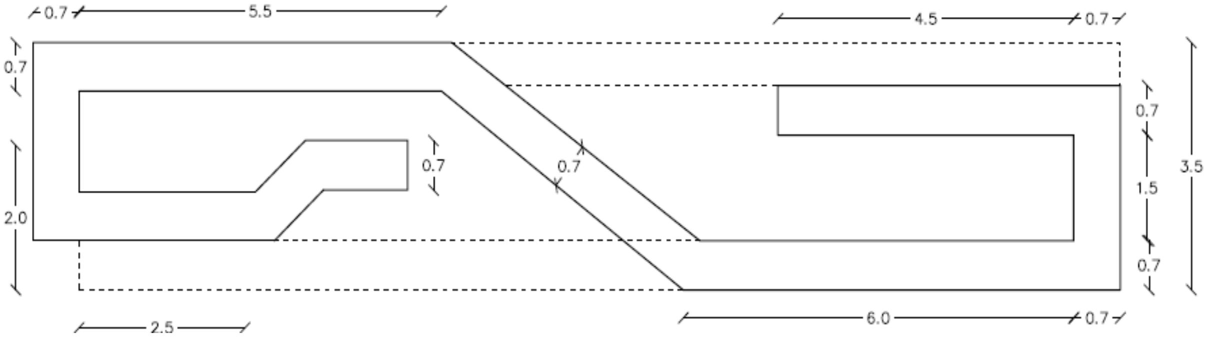
DETAIL G
SCALE 1.5 : 1



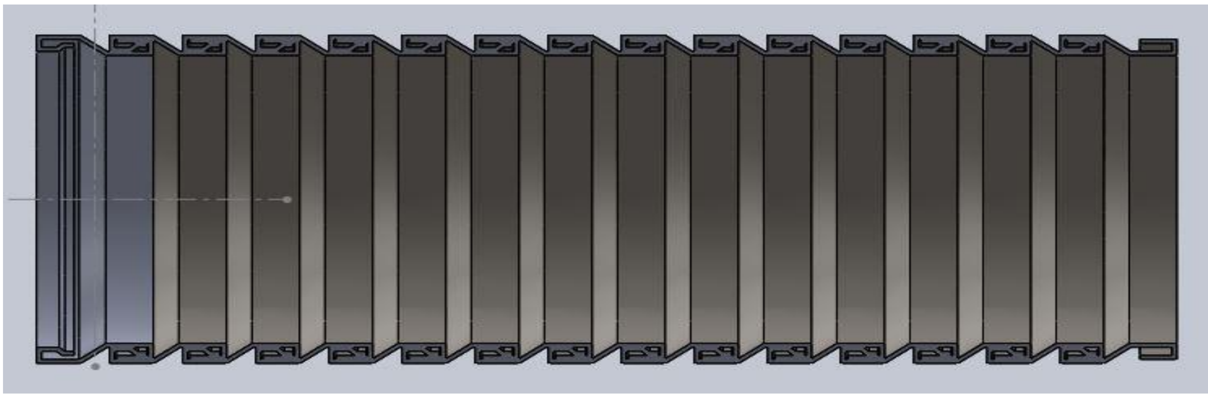
SECTION A-A



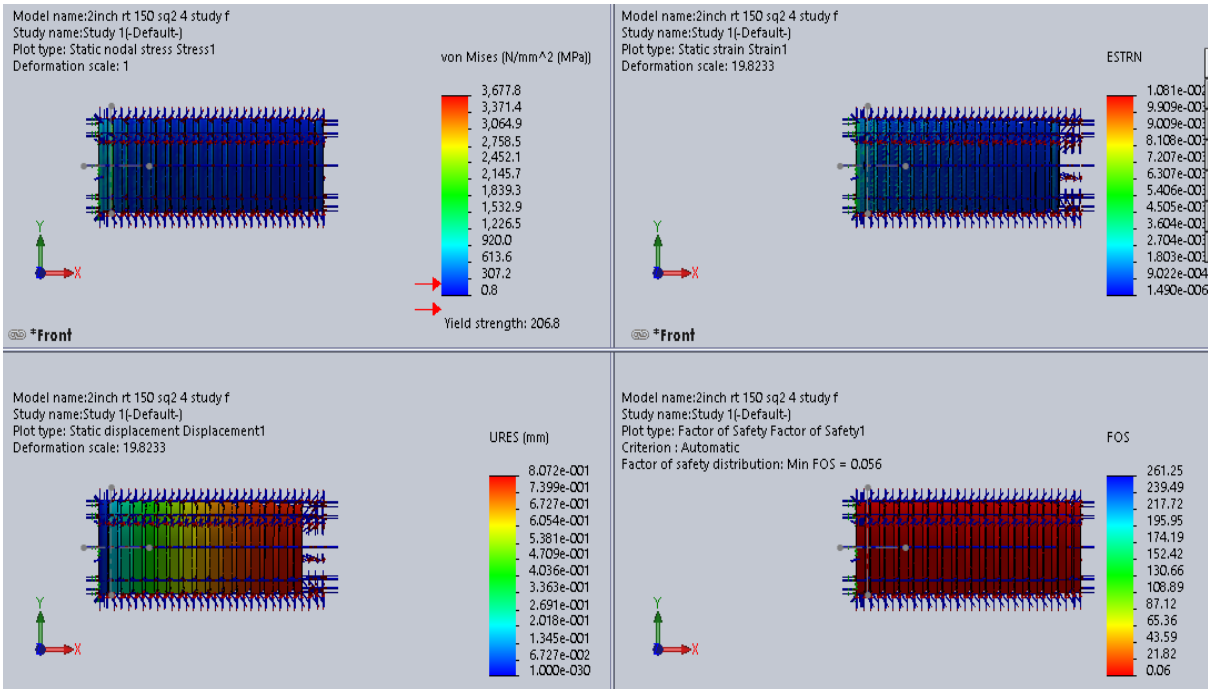
Resp. Department **Industrial Engineering and Management**	Technical Reference	Document type Assembly drawing		Document status Training		
Legal Owner KTU	Created by Balajee Govindaraj	Title, Supplementary title Interlock tube profile design - 1				
	Approved by Dr.Assoc.Prof.Marija Eidukeviciute		Rev A	Date 25.05.2015	Lang En	Sheet 1/4



A - 2 Dimensions of interlock profile design – 2



A – 2.1 Cross section of complete tube design – 2



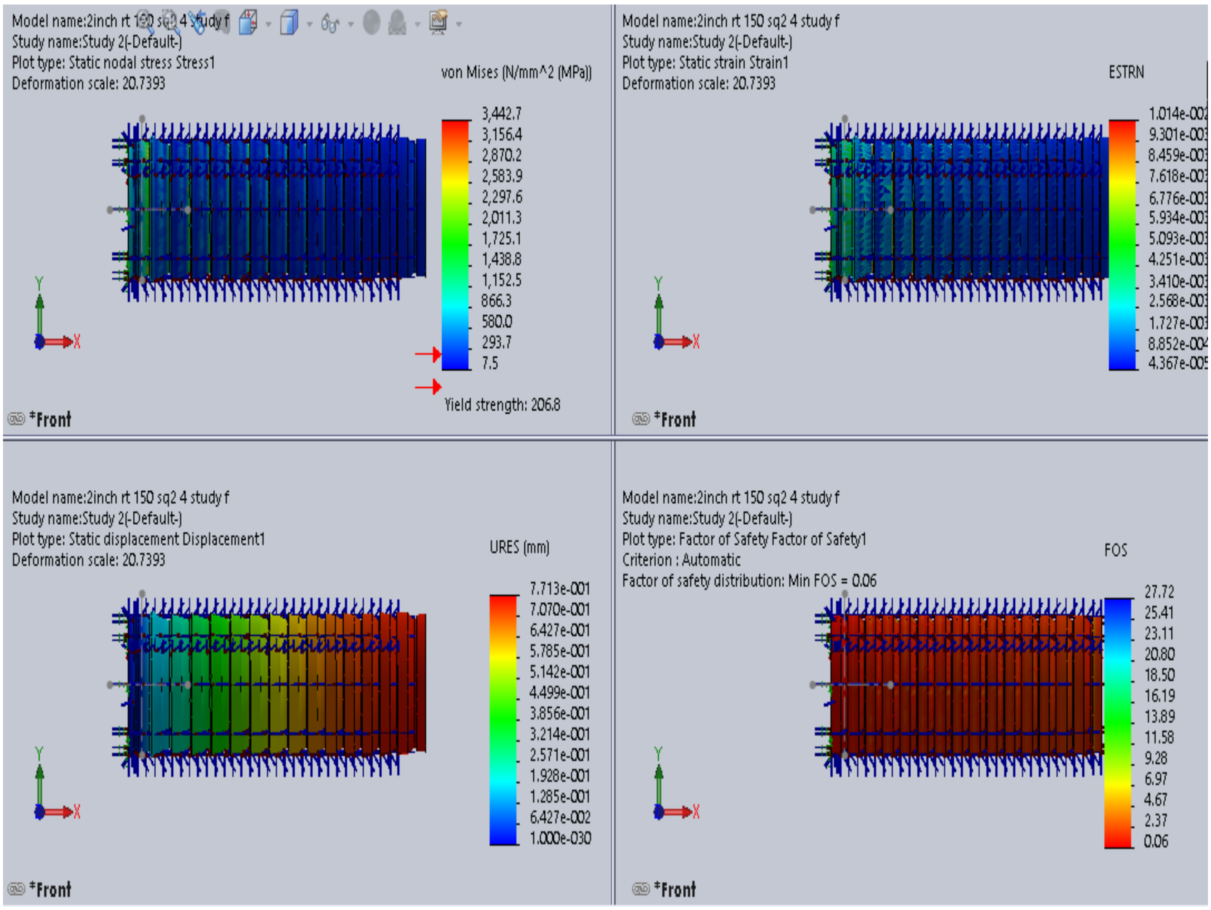
Model name:2inch rt 150 sq2 4 study f
Study name:Study 1(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 1

Model name:2inch rt 150 sq2 4 study f
Study name:Study 1(-Default-)
Plot type: Static strain Strain1
Deformation scale: 19.8233

Model name:2inch rt 150 sq2 4 study f
Study name:Study 1(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 19.8233

Model name:2inch rt 150 sq2 4 study f
Study name:Study 1(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Automatic
Factor of safety distribution: Min FOS = 0.056

A – 2.2 Compare results of stress, strain displacement and FOS - Pressure acting from outside: Pressure: 10 MPa and Temp: 30°C Mat: AISI 304



Model name:2inch rt 150 sq2 4 study f
Study name:Study 2(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 20.7393

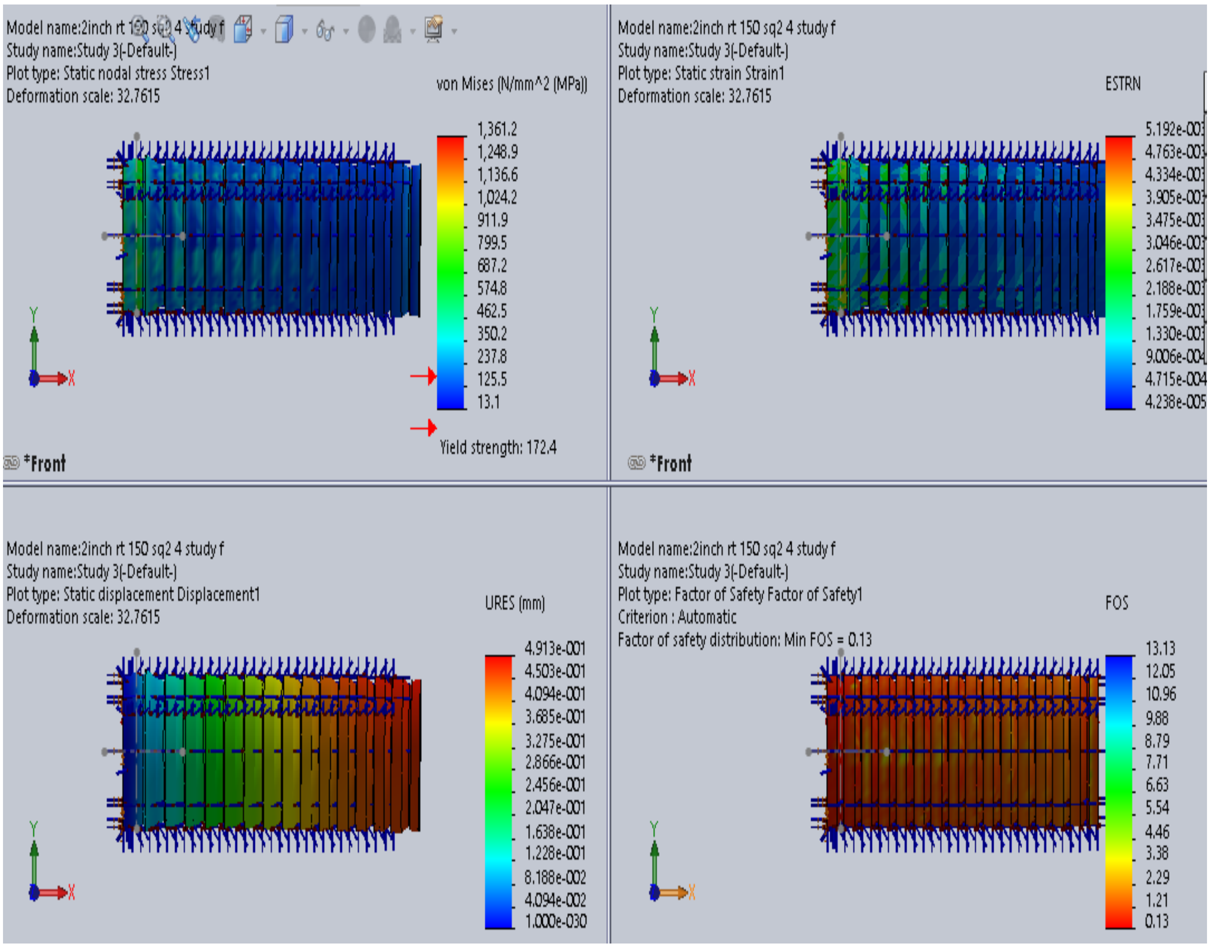
Yield strength: 206.8

Model name:2inch rt 150 sq2 4 study f
Study name:Study 2(-Default-)
Plot type: Static strain Strain1
Deformation scale: 20.7393

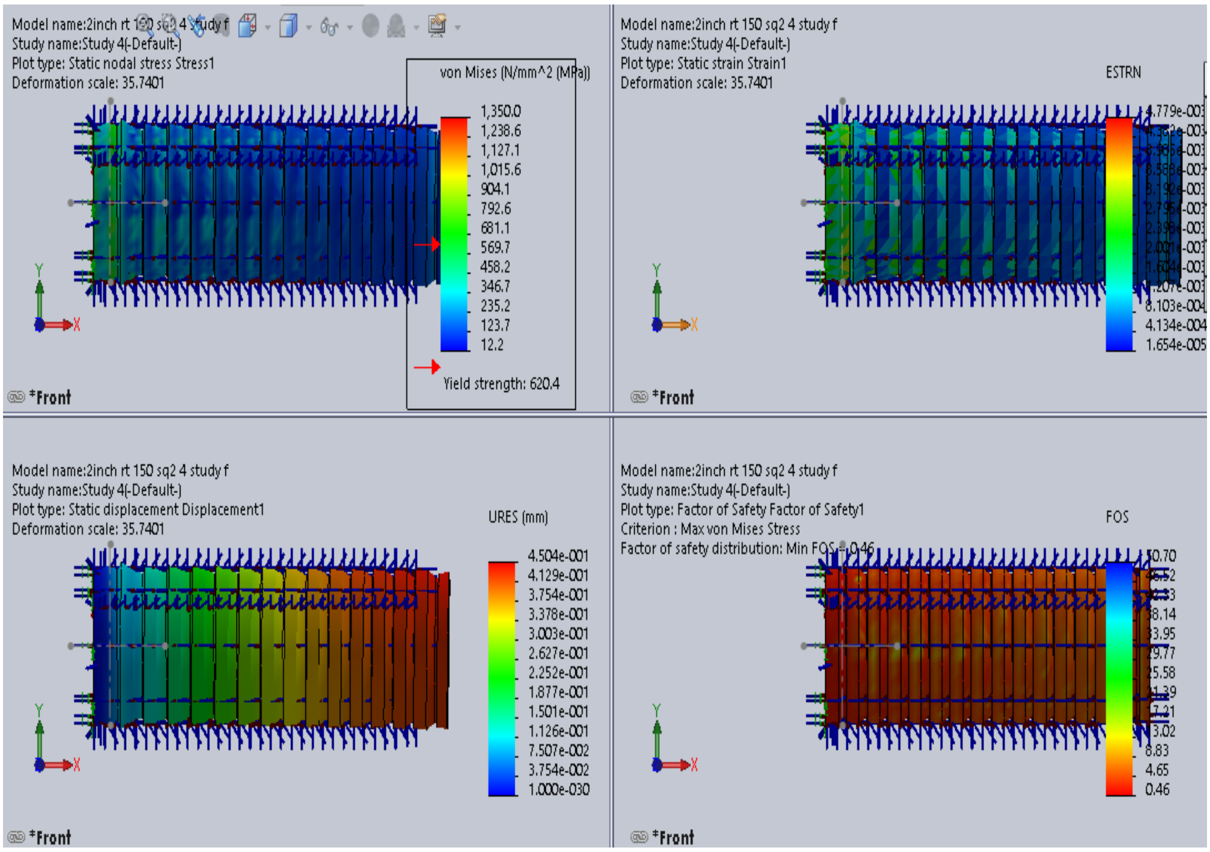
Model name:2inch rt 150 sq2 4 study f
Study name:Study 2(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 20.7393

Model name:2inch rt 150 sq2 4 study f
Study name:Study 2(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Automatic
Factor of safety distribution: Min FOS = 0.06

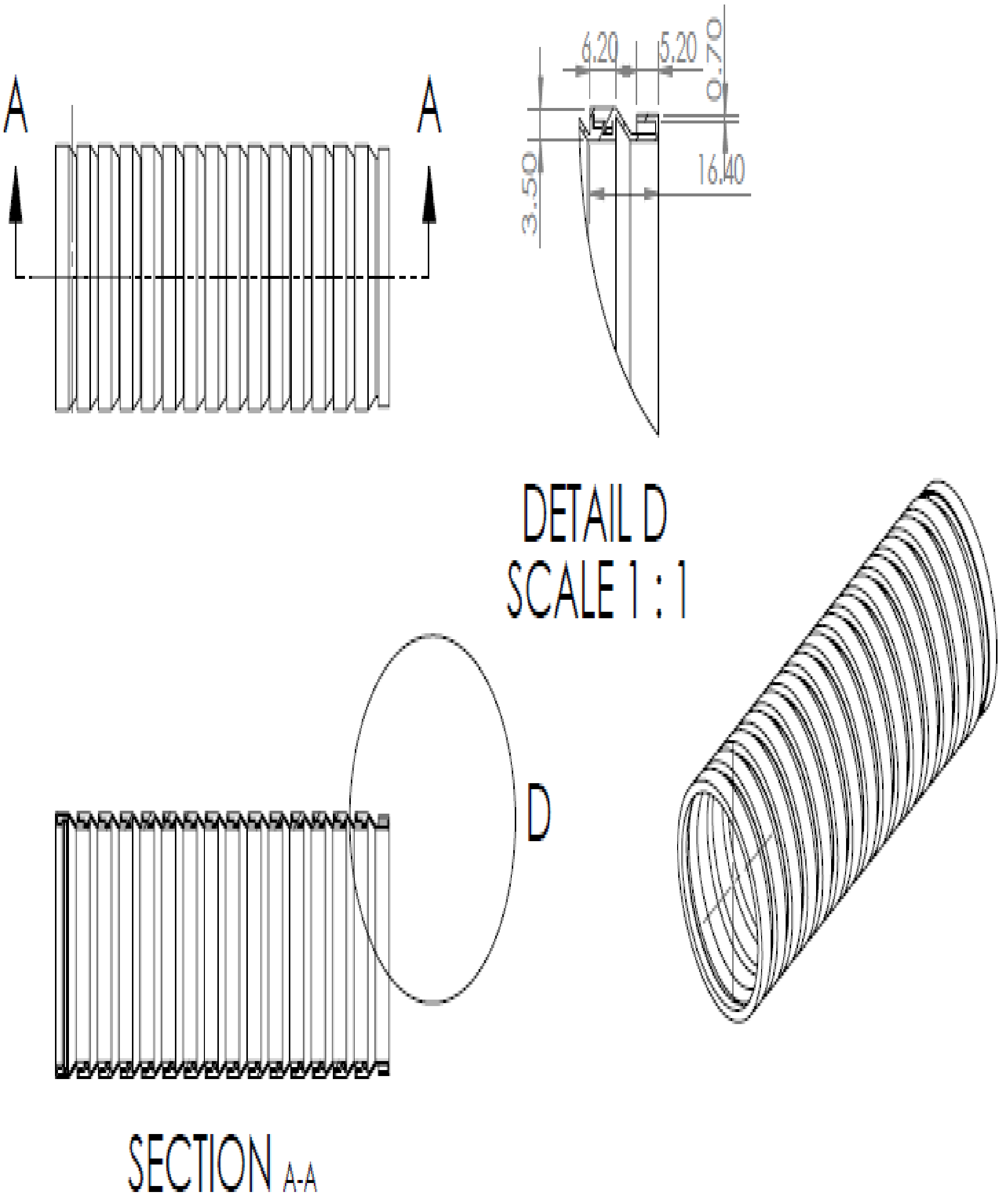
A – 2.3 Pressure acting from inside: Pressure: 10 MPa and Temp: 30°C Mat: AISI 304



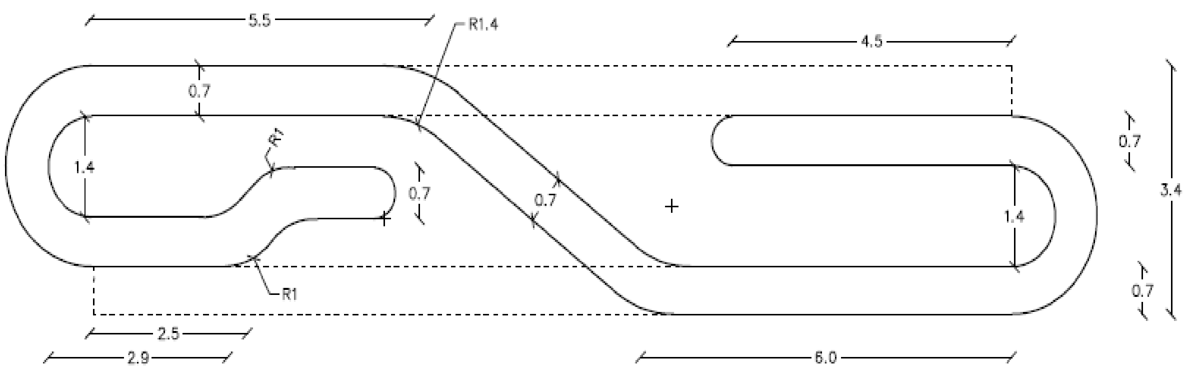
A – 2.4 Pressure: 10 MPa and Temp: 30°C Mat: AISI 316



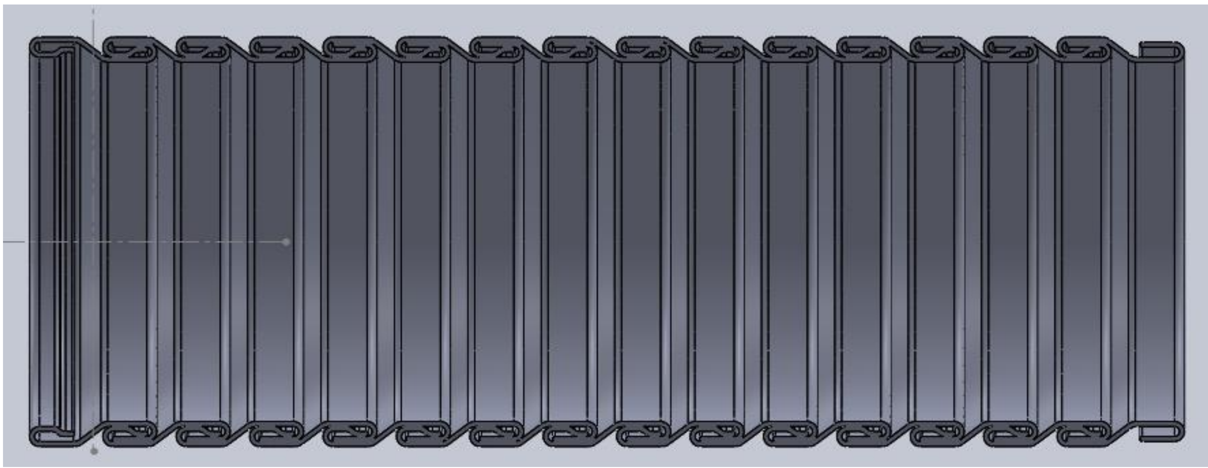
A– 2.5 Pressure: 10 MPa and Temp: 30°C Mat: Alloy steel



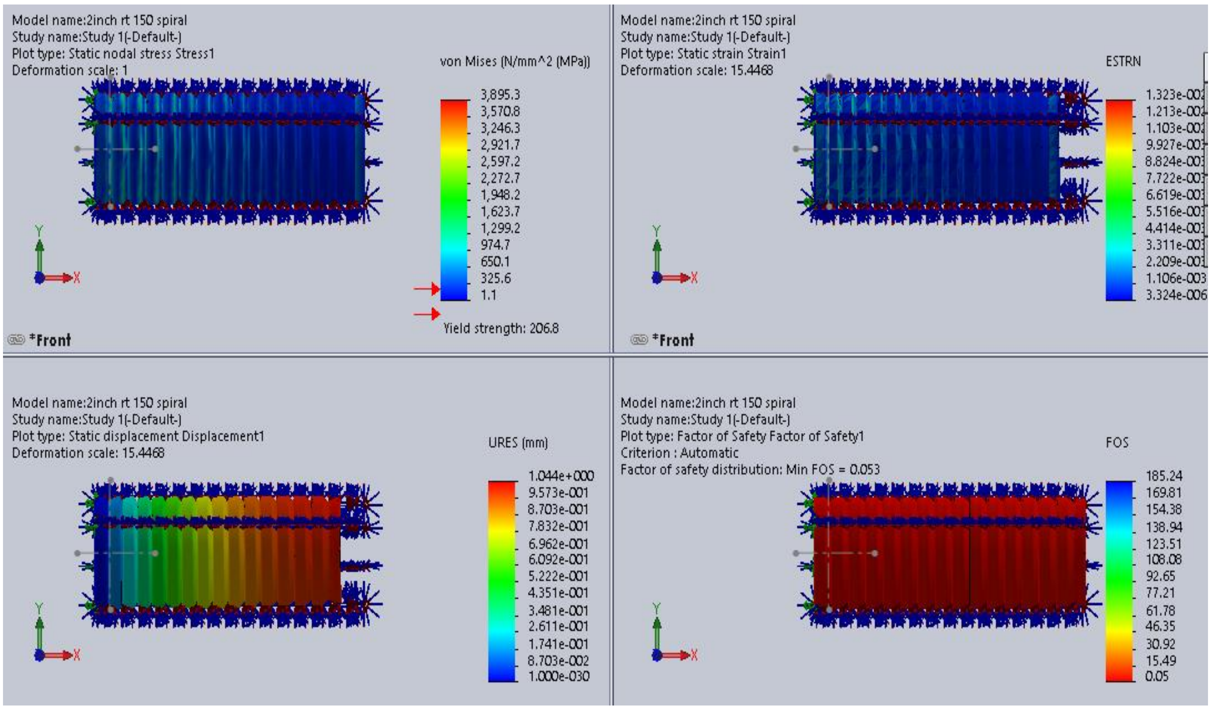
Resp. Department Industrial Engineering and Management	Technical Reference	Document type Assembly drawing	Document status Training
Legal Owner KTU	Created by Balajee Govindaraj	Title, Supplementary title Interlock tube profile design - 2	
	Approved by Dr.Assoc.Prof.Marija Eidukeviciute		Rev A Date 25.05.2015 Lang En Sheet 2/4



A – 3 Dimensions of interlock profile design – 3



A – 3.1 Cross section of complete tube design – 3



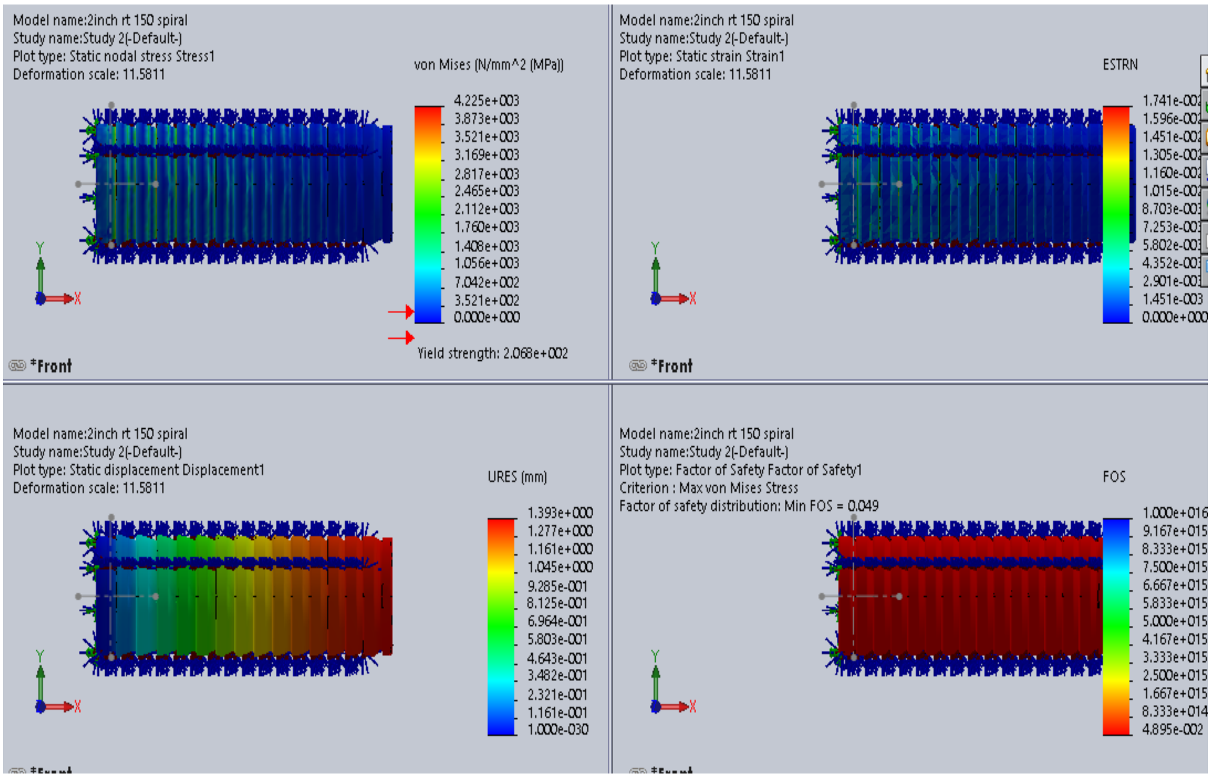
Model name:2inch rt 150 spiral
Study name:Study 1(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 1

Model name:2inch rt 150 spiral
Study name:Study 1(-Default-)
Plot type: Static strain Strain1
Deformation scale: 15.4468

Model name:2inch rt 150 spiral
Study name:Study 1(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 15.4468

Model name:2inch rt 150 spiral
Study name:Study 1(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Automatic
Factor of safety distribution: Min FOS = 0.053

A – 3.2 Compare results of stress, strain displacement and FOS - Pressure acting from outside: Pressure: 10 MPa and Temp: 30°C Mat: AISI 304

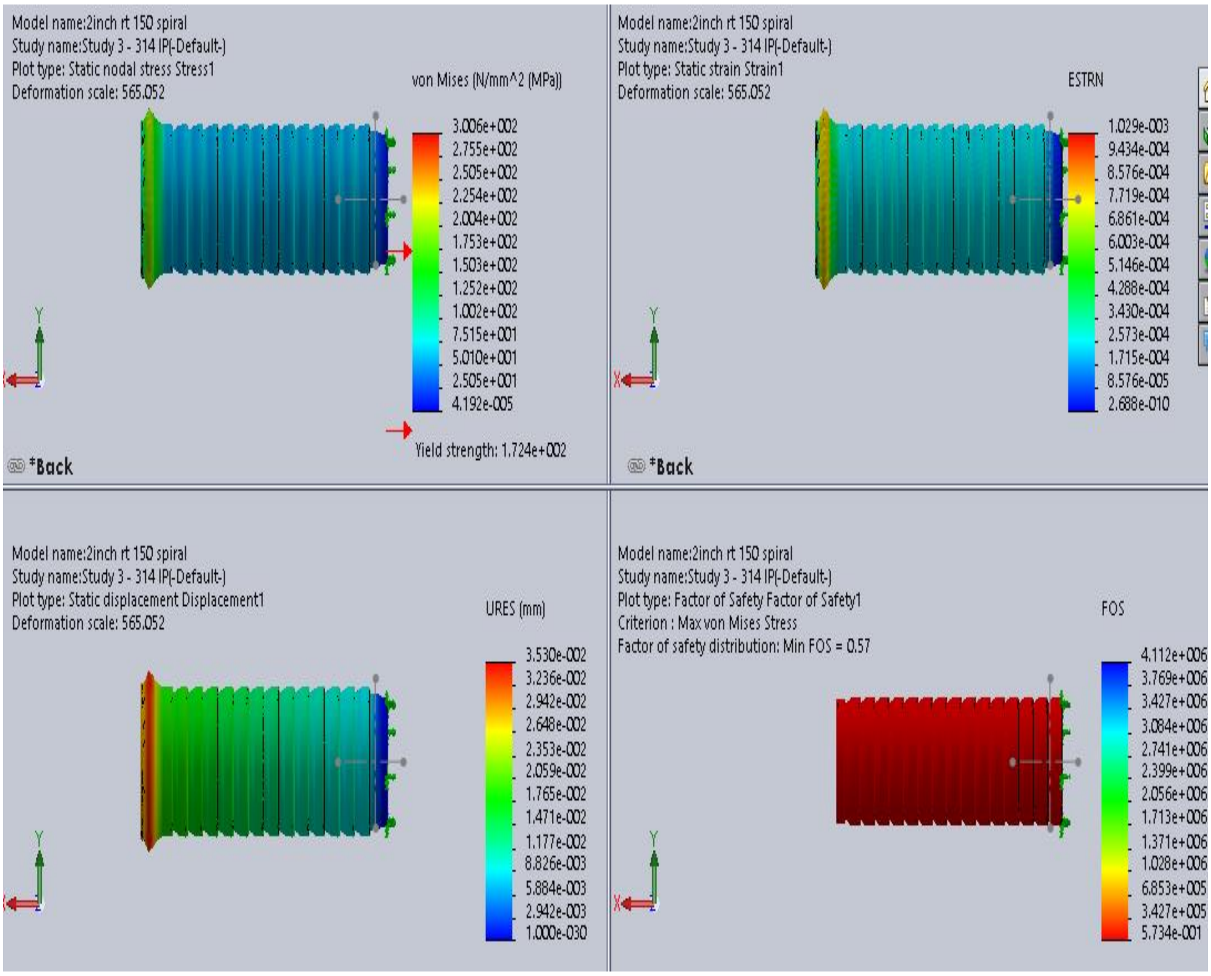

Model name:2inch rt 150 spiral
Study name:Study 2(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 11.5811

Model name:2inch rt 150 spiral
Study name:Study 2(-Default-)
Plot type: Static strain Strain1
Deformation scale: 11.5811

Model name:2inch rt 150 spiral
Study name:Study 2(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 11.5811

Model name:2inch rt 150 spiral
Study name:Study 2(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Max von Mises Stress
Factor of safety distribution: Min FOS = 0.049

A – 3.3 Pressure acting from inside: Pressure: 10 MPa and Temp: 30°C Mat: AISI 304

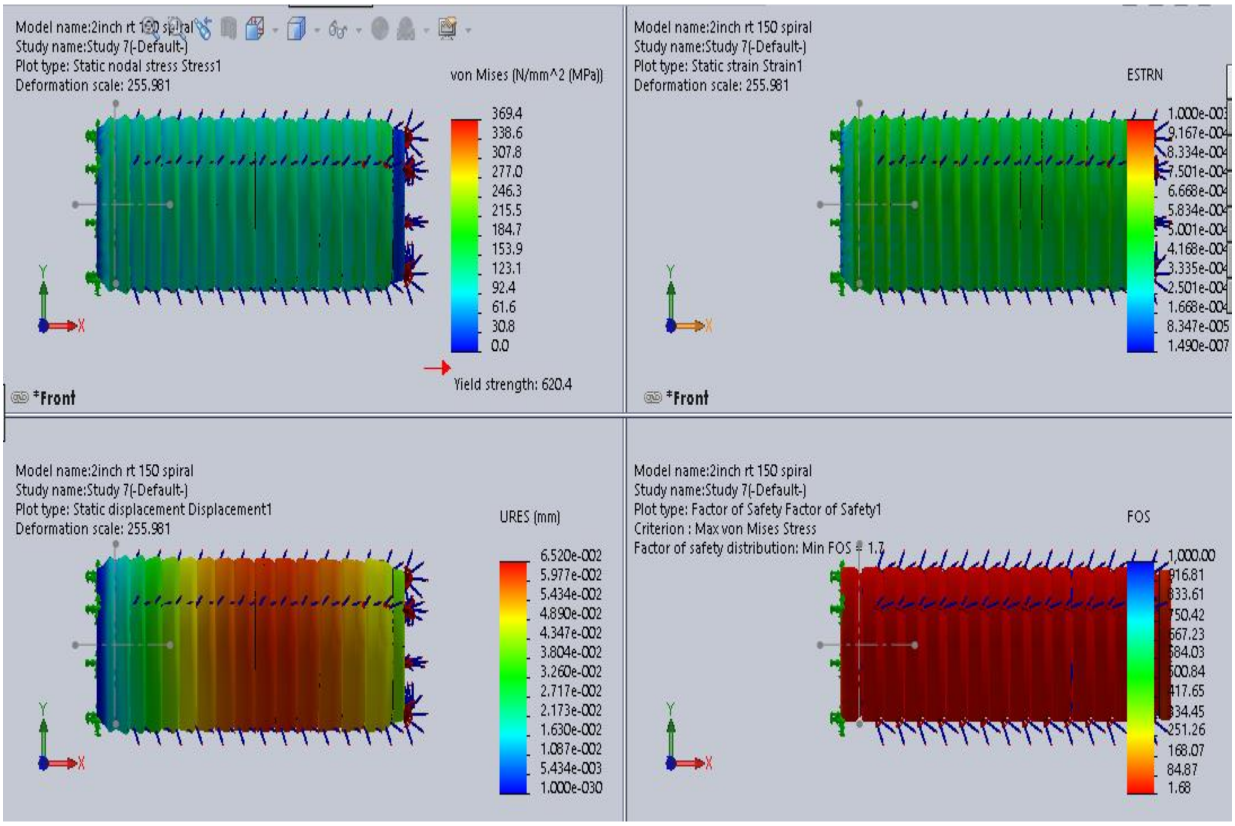

Model name:2inch rt 150 spiral
Study name:Study 3 - 314 IP(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 565.052

Model name:2inch rt 150 spiral
Study name:Study 3 - 314 IP(-Default-)
Plot type: Static strain Strain1
Deformation scale: 565.052

Model name:2inch rt 150 spiral
Study name:Study 3 - 314 IP(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 565.052

Model name:2inch rt 150 spiral
Study name:Study 3 - 314 IP(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Max von Mises Stress
Factor of safety distribution: Min FOS = 0.57

A – 3.4 Pressure: 10 MPa and Temp: 30°C Mat: AISI 316


Model name:2inch rt 150 spiral
Study name:Study 7(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 255.981

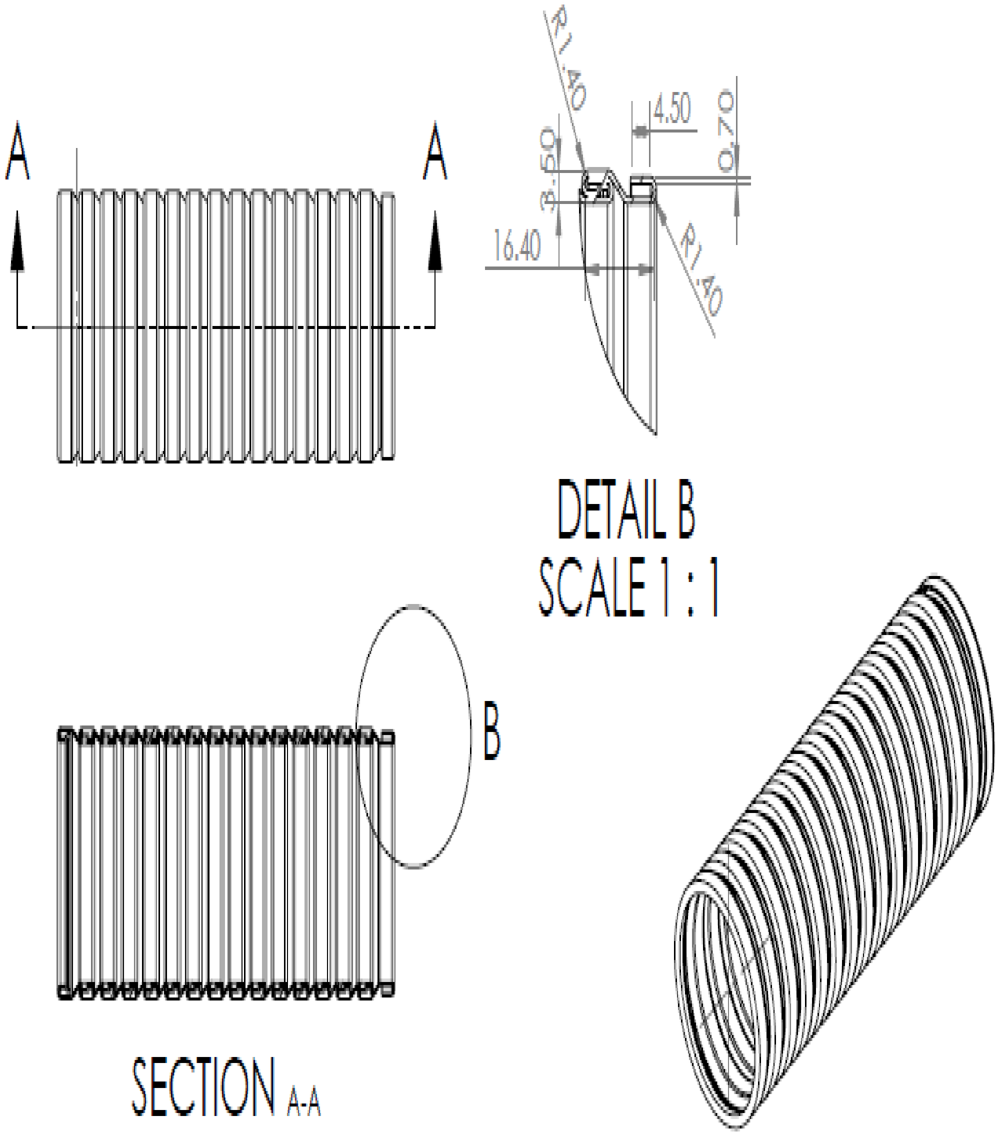
Yield strength: 620.4

Model name:2inch rt 150 spiral
Study name:Study 7(-Default-)
Plot type: Static strain Strain1
Deformation scale: 255.981

Model name:2inch rt 150 spiral
Study name:Study 7(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 255.981

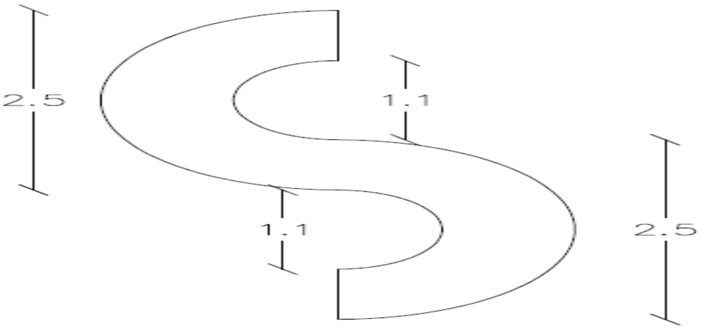
Model name:2inch rt 150 spiral
Study name:Study 7(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Max von Mises Stress
Factor of safety distribution: Min FOS = 1.7

A – 3.5 Pressure: 10 MPa and Temp: 30°C Mat: AS

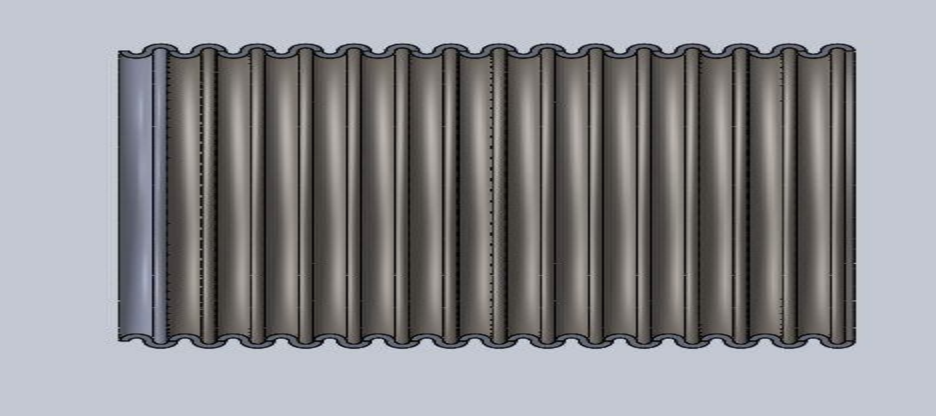


Resp. Department Industrial Engineering and Management	Technical Reference	Document type Assembly drawing		Document status Training	
Legal Owner KTU	Created by Balajee Govindaraj	Title, Supplementary title Interlock tube profile design - 3			
	Approved by Dr.Assoc.Prof.Marija Eidukeviciute		Rev A	Date 25.05.2015	Lang En
					Sheet 3/4

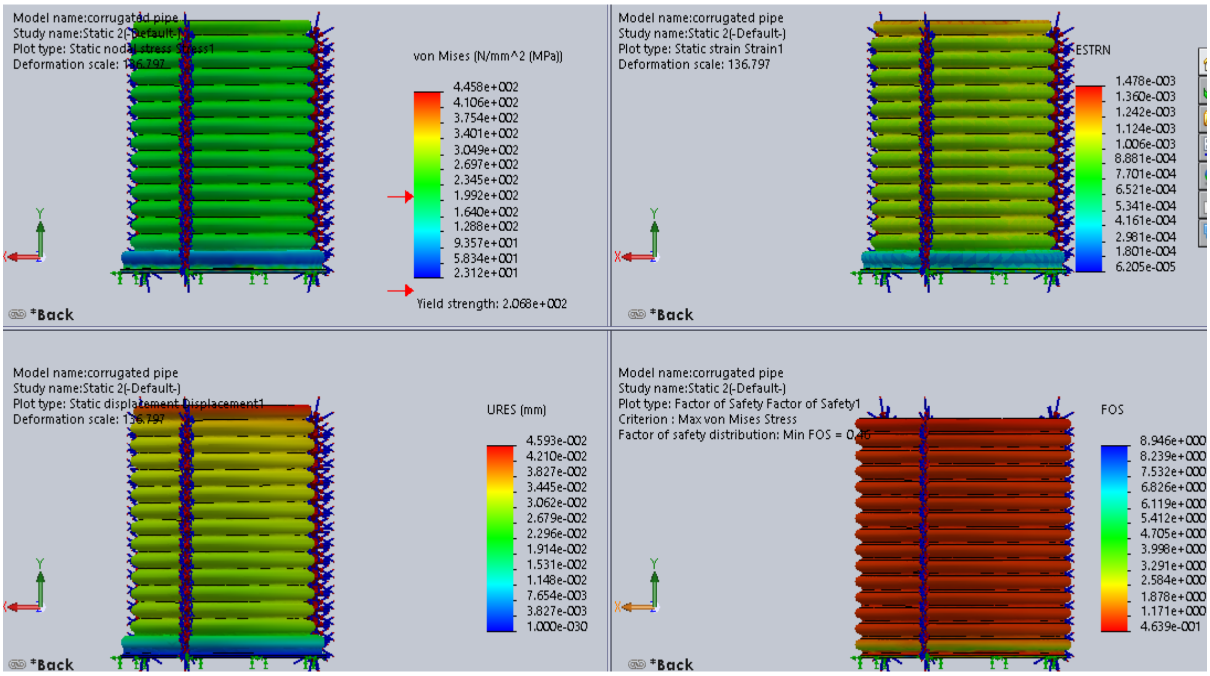
Corrugated pipe design:



A – 4 Dimensions of CP design



A – 4.1 Cross section of CP tube



Model name:corrugated pipe
Study name:Static 2(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 136.797

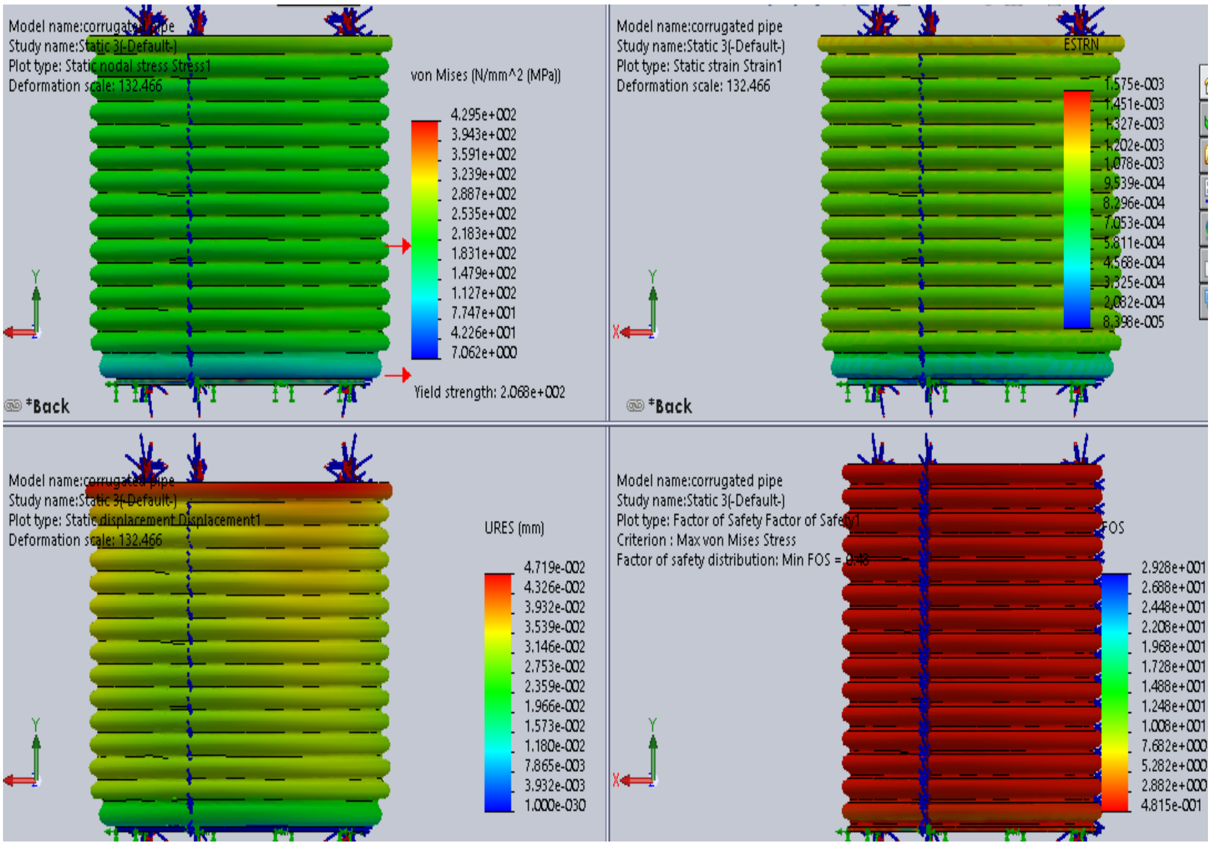
Model name:corrugated pipe
Study name:Static 2(-Default-)
Plot type: Static strain Strain1
Deformation scale: 136.797

Model name:corrugated pipe
Study name:Static 2(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 136.797

Model name:corrugated pipe
Study name:Static 2(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Max von Mises Stress
Factor of safety distribution: Min FOS = 0.46

Yield strength: 2.068e+002

A – 4.2 Compare results of stress, strain displacement and FOS - Pressure acting from outside: Pressure: 10 MPa and Temp: 30°C Mat: AISI 304



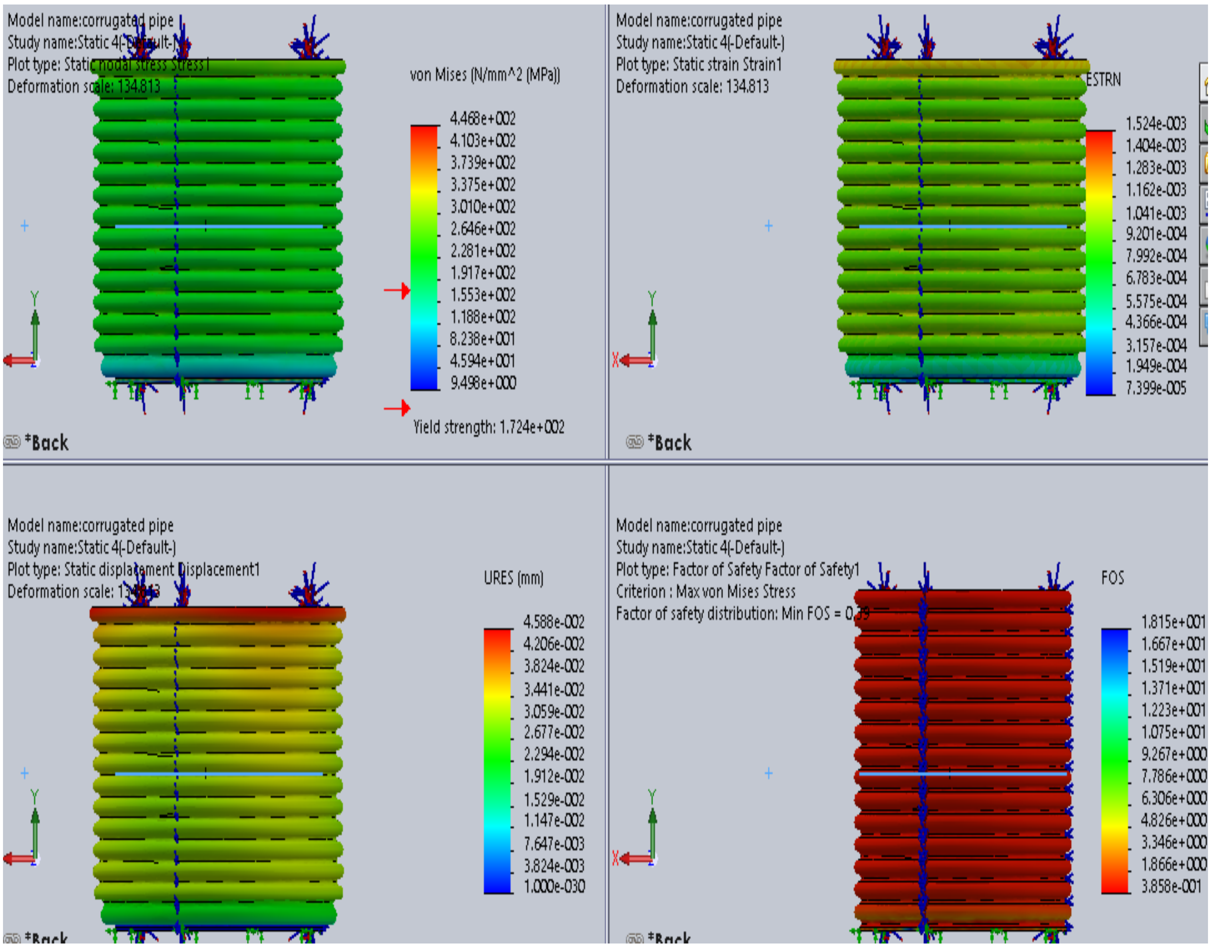
Model name:corrugated pipe
Study name:Static 3(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 132.466

Model name:corrugated pipe
Study name:Static 3(-Default-)
Plot type: Static strain Strain1
Deformation scale: 132.466

Model name:corrugated pipe
Study name:Static 3(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 132.466

Model name:corrugated pipe
Study name:Static 3(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Max von Mises Stress
Factor of safety distribution: Min FOS = 0.48

A – 4.3 Pressure acting from inside: Pressure: 10 MPa and Temp: 30°C Mat: AISI 304



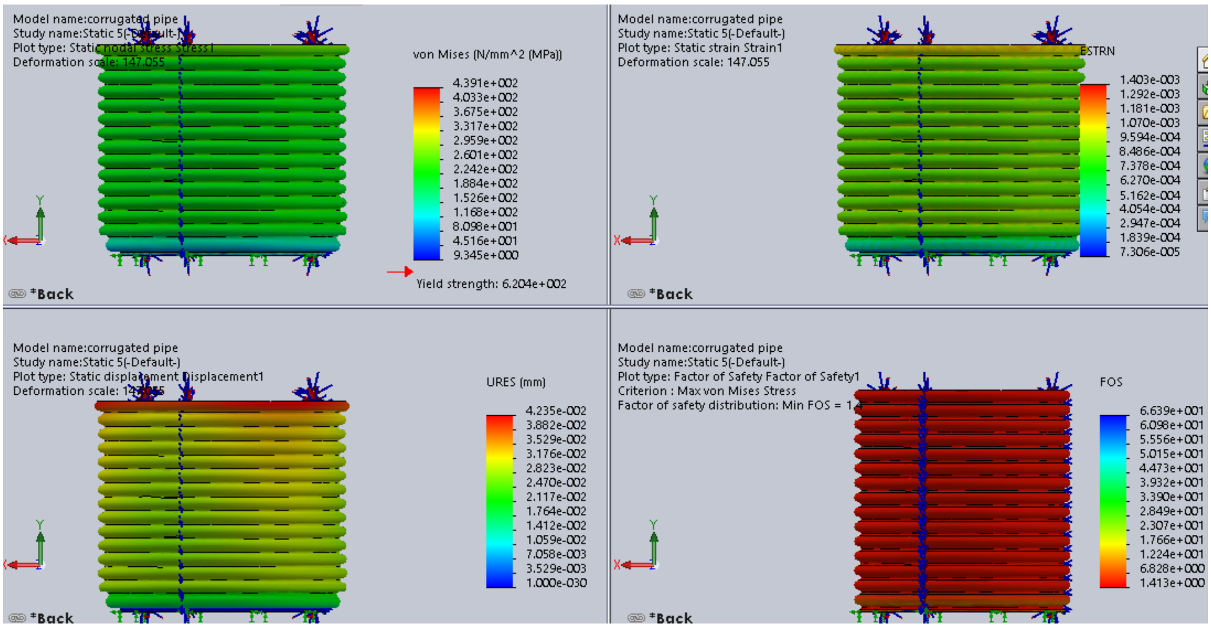
Model name:corrugated pipe
Study name:Static 4(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 134.813

Model name:corrugated pipe
Study name:Static 4(-Default-)
Plot type: Static strain Strain1
Deformation scale: 134.813

Model name:corrugated pipe
Study name:Static 4(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 134.813

Model name:corrugated pipe
Study name:Static 4(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Max von Mises Stress
Factor of safety distribution: Min FOS = 0.39

A – 4.4 Pressure: 10 MPa and Temp: 30°C Mat: AISI 316



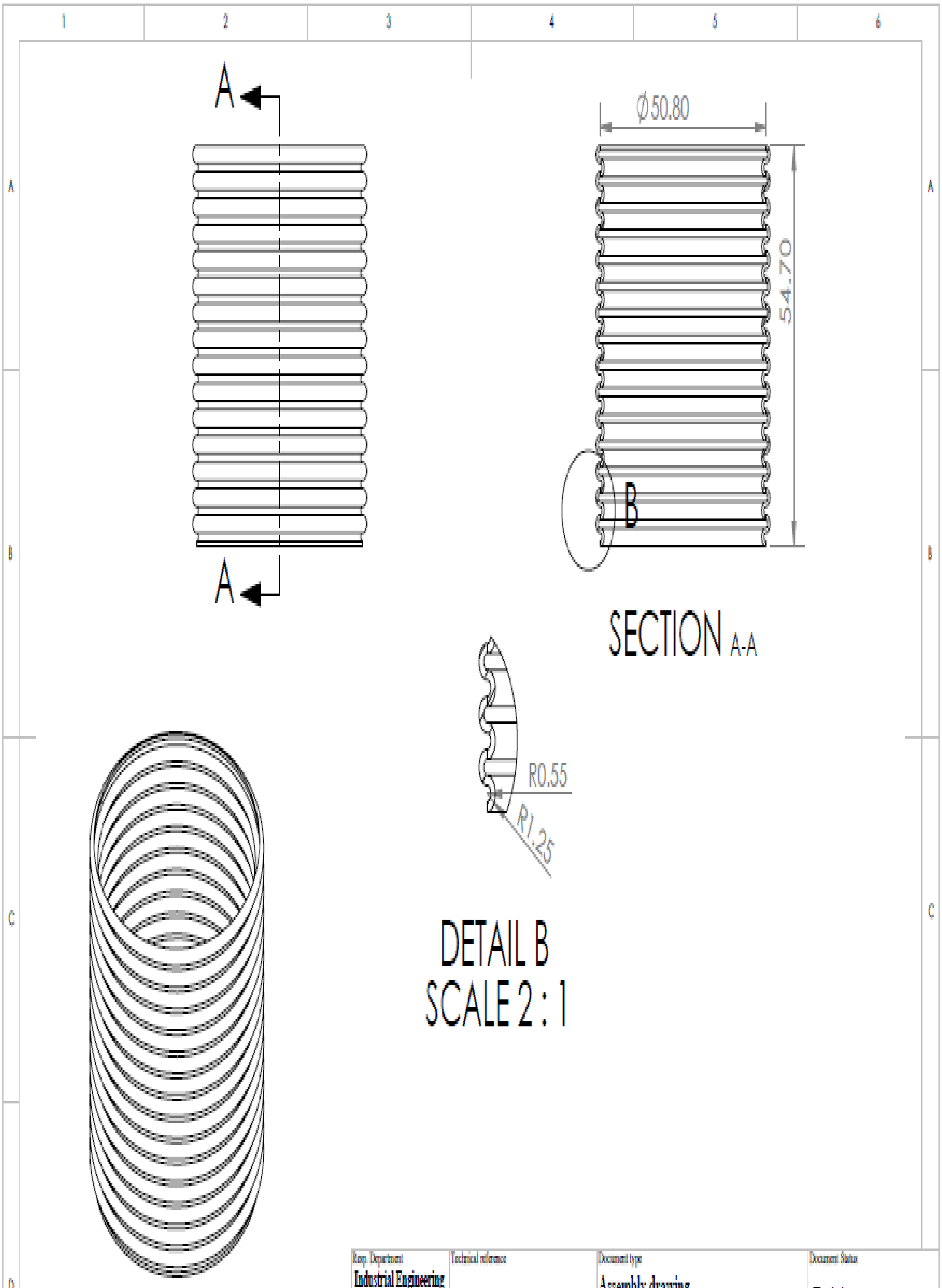
Model name:corrugated pipe
Study name:Static 5(-Default-)
Plot type: Static nodal stress Stress1
Deformation scale: 147.055

Model name:corrugated pipe
Study name:Static 5(-Default-)
Plot type: Static strain Strain1
Deformation scale: 147.055

Model name:corrugated pipe
Study name:Static 5(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 147.055

Model name:corrugated pipe
Study name:Static 5(-Default-)
Plot type: Factor of Safety Factor of Safety1
Criterion : Max von Mises Stress
Factor of safety distribution: Min FOS = 1.4

A – 4.5 Pressure: 10 MPa and Temp: 30°C Mat: AS



Resp. Department Industrial Engineering and Management	Technical reference	Document type Assembly drawing	Document Status Training
Legal owner KTU	Created by Balajee Govindaraj	Title, Supplementary title Corrugated metal pipe design	
	Approved by Dr.Assoc.Prof.Marija Eidukeviciute		Rev A

Date	Lang	Sheet
25.05.2015	En	4/4