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Polyurethane sealing discs on cleaning pigs; characterisation and dynamic behaviour

Master Thesis by

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Abstract

Pipeline pigging enhances flow rate and corrosion control. Pigging is made possible by the sealing element of the pig, of which polyurethane is the chief material used. Polyurethane raw materials are; polyols, isocyanates, water, methylene chloride, catalyst, chain extenders, colourants, air and additives. These raw materials are combined on 'systems' rather than a straight-forward formula, and are formulated to achieve predetermined properties in order to suit end applications.

The main aim of this thesis is to develop a deeper understanding of keeping pipeline as much as possible to the as-built condition, as efficient and predictable seal discs facilitate safe and efficient pigging. Keeping maximum continuous flow reduces cost and also increase the life span of the pipeline. This is achieved by the understanding precisely shore grade 65, 75 and 85 used for pigging operations. The structure of this thesis is divided into four parts.

The first part involves the determination of the material properties of shore grade 65, 75 and 85 at temperatures of 20°C, 40°C, 60°C, 70°C and 80°C. The material properties of shore grade 65, 75 and 85 are achieved from the stress-strain curve of the polyurethane at the different temperature using tensile test machine. Shore grades are heat treated to the required temperature of minimum of 12 hours in an oven or refrigerator before the tensile test.

The second part of the thesis is using the stress - strain data as an input into finite element material database, hence finite element model of the seal discs geometry is created to determine resulting deflection, static reacting forces on the wall. This was achieved by the application of step incremental displacement on the pig discs into the 8’’ pipeline in order to generate the static behavior of pig of shore grade 65, 75, & 85 at different temperature.

The third part of the thesis involves the use of stress-strain data to perform transient dynamic analysis of seal discs with shore grade 65, 75 and 85 at 20 °C. This is to determine resulting deflection, and “kinetic reacting forces on the wall”. This was achieved by the application of differential pressure on the pig so as to drive it into the 8’’ pipeline in order to generate the dynamic behavior of pig (shore 65, 75, & 85) at 20 °C.

Finally, a verification test on the time travel of pig (shore grade 65, 75 & 85) on a test rig 8’’x12m long was performed in IK AS facility Forus.

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List of Nomenclatures

Abbreviations

MDI Methylene bisdiphenylisocyanate

TDI Toluene di-isocyanate

NCO/OH Isocyanate and polyol ratio

PU Polyurethane

PTMEG Polytetra methylene ether glycol

Alphabet

A_o- Initial cross sectional area

D - Flexural rigidity

e – Elongation

E - Young modulus

F- Tensile force

F_u- Tensile force at rapture

h - Thickness

I - Strain invariants

J - Volumetric ratio

L_o- Original gauge length

M – Moment

n - Local normal

p - Distributed load (force per unit area)

s - Local tangent at perimeter

S - Shear force

w – Displacement, deflection

W- Strain energy potential or strain energy

Symbols

σ- Stress, tensile stress

σ_0 - Engineering stress

σ_u- Ultimate tensile strength

ε - Strain

ϕ - Stress function

r - Radial coordinate

θ - Angular coordinate

ΔL- Change in gauge length

ΔT- Temperature change

$\boldsymbol{v}$- Poisson ratio

δW - Work performed

δH - heat that flows

δU -internal energy

δK - Kinetic energy

U_0 - Strain energy density

λ_1 , λ_2 and λ_3 are the principal stretches

1. Introduction

1.1 Background

The world's population is increasing, so also industries are increasing, due to the fact that they are set-up to meet the needs of the growing population. Energy is needed to keep industries functioning and also serves man's daily need. Technological advancement has taken the search for cheap, clean and reliable energy to remote places that were difficult or in-accessible in the primitive age.

Oil and gas serves as the major source of energy (IEA, 2014), although there are other sources of renewable energy that are in consideration.

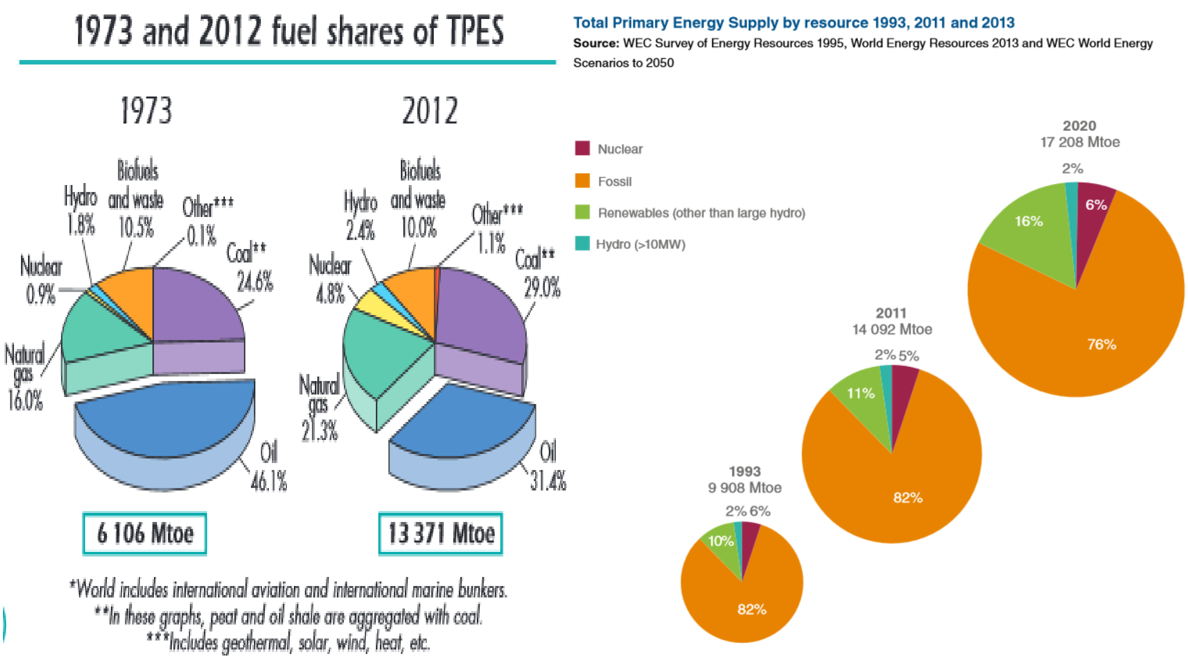


Figure 1.1: Primary energy supply. (IEA, 2014) and (Gadonneix, 2013)

World energy resources data shows that over fifty percent of energy are derived from oil and gas (IEA, 2014) and over eighty percent of energy are derived from fossil fuel (Gadonneix, 2013). Once the oil and gas is separated in offshore/onshore facility, it is sent to refineries and processing plant through pipeline.

In the world we live in today, pipelines are used to transport all manner of petroleum product from one point to another. Pipeline could be short and could also run into several thousands of kilometers. Millions of lives are affected by the ability to maintain flow through pipelines that cross over land and undersea to deliver oil and gas products. Coupled with the economic drive to maintain product flow, the importance of this task has set-up a whole industry to ensure pipeline integrity.

The Norwegian gas transportation system consists of 4,900 miles (7,800 km) of offshore pipelines and three large gas processing plants, which are integrated into a single network. It is a complex network, which is the largest offshore transportation system in the world (Langelandsvik et al., 2009).

Today the need for installed pipeline around the world to continue to serve it function is a major challenge. For this to be achieved, pipelines should retain as much as possible its as-built conditions. The efficiency of installed pipeline depends on (Landes, 1983);

- Continuous flow
- Minimizing corrosion
- Minimum pumping cost

Pigging of pipeline is one of the processes of keeping pipeline in its as-built condition, which its primary material (polyurethane) behaviour, which is the subject of thesis. Understanding of this material behaviour, Polyurethane in particular shore grade 65, 75 and 85 with temperature change is a key in making pipeline to retain its as-built condition.

1.2 Objectives of thesis

The main aim of this thesis is to develop a deeper understanding of keeping pipeline as much as possible to the as-built condition, as efficient and predictable seal discs facilitate safe and efficient pigging. In another words, keeping maximum continuous flow as that of the design state, this tends to reduce cost and also increase the life span of the pipeline. This will be achieved by the understanding of the material (polyurethane) for sealing and cleaning the pipeline during pigging operation. The structure of this thesis is divided into three parts.

The first stage involves the determination of the material properties of polyurethane for shore grade 65, 75 and 85 at temperatures of 20°C, 40°C, 60°C, 70°C and 80°C. The material properties of shore grade 65, 75 and 85 will be achieved from the stress-strain of the polyurethane at the different temperature using the aid of tensile test machine, in addition of heat treating the PU at a minimum of 12 hours in a furnace or refrigerator. In other word, these shore grade will be subjected to axial tension test, from which the stress-strain of these shore grade will be derived. The stress-strain data of every engineering material represents the material behavior, hence that of shore grades 65, 75 and 85.

The second part of this thesis is using the stress -strain curves as an input into finite element material database, hence finite element model is created of the seal discs geometry to perform a static analysis in order to determine resulting deflection, static reacting forces on the wall and plot curves for shore grades 65, 75 and 85 and at temperatures of 20°C, 40°C, 60°C, 70°C and 80°C. This will be achieved by incremental displacement on the pig discs into the 8 inches pipeline for the generation of the static behaviour of the pig.

The third phase of the thesis involves the use of stress-strain data as an input into finite element material data base, hence to perform transient dynamic analysis of seal discs with shore grade 65, 75 and 85 at 20 °C. This is to determine resulting deflection and the reaction forces on the pipe wall. Plot curves for different shore grade and temperatures.

The final stage involve verification of the physical model with FEA model. This involves the FE model to be compared with the physical test rig of 8’’X12m long in IK AS laboratory.

1.3 Outline of Thesis

The thesis is organized in nine (9) chapters based on the objective listed in Chapter 1.2 of this thesis. The subsequent chapters are laid out in the following logical order;

Chapter 2: Pigging - This chapter presents an introduction to pigging. It also covers extensively the types of pigs, pig selection criteria, and also the reasons for pigging operations

Chapter 3: Polyurethane - This chapter covers brief introduction to polyurethane, which is the chief material of this thesis, then also covers extensively the raw material for PU formulation.

Chapter 4: Plate theory – This chapter presents an introduction of plate theory, and an overview of the assumptions of plate theory, the classical equation of the theory and also the boundary conditions in plate theory. In addition, an extensive study of isotropic material and hyperelastic material models was covered.

Chapter 5: Tensile test – This chapter presents the tensile properties of polyurethane material, factors influencing polyurethane properties, tensile test equipment and conditioning equipment, and final tensile test results for shore grade 65, 75 and 85 at temperature of 20 °C, 40°C, 60°C, 70°C and 80°C.

Chapter 6: Design methodology – This chapter presents the relevant steps and procedure which was followed in designing shore grade 65, 75 and 85 pig and also the design requirement and assumption in the use of ANSYS software for both static and dynamic analysis.

Chapter 7: Static analysis result of polyurethane - This chapter presents the results of static analysis of shore grade 65, 75 and 85 pig discs at different temperature of 20 °C, 40°C, 60°C, 70°C and 80°C.

Chapter 8: Transient dynamic analysis result of polyurethane – This chapter presents the result of the dynamic analysis of shore grade 65, 75 and 85 pig discs at temperature 20 °C.

Chapter 9: Conclusion, recommendation and further works - This chapter summarizes the result of the analysis presented in this thesis and also presents the recommendations for further works.

2. Pipeline Pigging

2.1 Introduction

Pig is a device that is propelled down pipelines by the aid of fluid or external pressure to seal and clean the interior of the pipeline. Other functions of pig are to check pipeline thickness, roundness, corrosion, leaks and other internal defect that may either restrict the flow of oil and gas, or pose a potential safety risk for the operation of the pipeline. The process of launching pig into pipeline is known as 'pigging' the pipeline. The main component of the pigs is the seal, which material behaviour is the subject of this thesis. The seal of pigs are designed so that it gives a positive interference with the wall of the pipeline. Pig is launched into the pipeline by pressure, once installed in the pipeline it is driven by differential pressure. The driven pressure varies depending on the state of the pipeline. For un-commissioned lines, water for flooding, dry air or nitrogen gas is used to create the differential pressure. Pipeline in operation are sensitive, driving fluid should not contaminate the transporting fluid, and this implies that transporting fluid are used to transport the pig (e.g. gas, crude oil).

Movement of pig depends on the force generated by the fluid behind it. The pig moves when the force of it propagation is greater than the opposing frictional force, and then the pig will move in the direction of the propagation force.

The pressure that is required for the pig to begin to move is known as the 'break out 'or 'stiction' pressure. This pressure is greater than the pressure required to maintaining movement and is characterized by pressure rise followed by a drop to plateau for the pig launching operation.

Pigs run in pipeline depends on the shape of the seal, the material the seal is made of and also the number of seals in the pig set-up, all these will determine whether the pig can either be run in one (single) direction or run backwards or forwards through the line; bidirectional pig.

Pigs that are only run in one direction are known as unidirectional pigs. These pigs have polyurethane sealing elements of the cup or cone design. These types of pigs are used for pipelines that are in general easy to pig, Pipeline that the pig will not struck inside it.

The sealing elements of bidirectional seals are flat. These elements provide dual seals at both direction, and therefore giving more adaptability in the previously un-pigged lines. In some special cases, additional sealing elements are added to pigs, leading to a better sealing along the pipeline walls. This will encourage higher differential pressure require to drive the pig.

The additional elements are added to the pig set-up, for example discs or, wheels for large diameter pig. This added element ensures that the pig is centralized during pigging.

Pig's outer diameter dimension is a key property of its function. Its outer diameter is same as, or slightly larger than the internal diameter of the pipe. Table 2.1shows the characteristics of pig of simplified bi-directional disc pig (Davidson, 2002).

Component	Size
Sealing Disc Diameter	102 % to 105% Pipeline ID
Support Disc Diameter	99% Pipeline ID
Pig Assembly Length	1.5 X Pipeline ID

Table 2.1: General pig characteristics

Most standard pigs are design to bypass a small portion of the propelling medium during its run. The bypass is average between 2% to 15%, this is a function of the pig type. Often, pigs bypass and leave as much as 25% of the product in the pipeline after displacement run (Winters, 2014)

2.2 Types of pigs

Pigs are integrated for the maintenance of pipeline infrastructure, their primary function is to make the pipeline as much as possible retain or reverse to its as-built condition. They are broadly classified into two types; cleaning pigs and intelligent pigs (which are also called in-line inspection tools). Below are the major types of pigs.

2.2.1 Batching Pig

The most common type of this pig seal are in the form of cup or sphere. They are use in the separation of two different products in the pipeline. These products are mostly gas and liquid. The cup batching pigs are used for pigging operations such as filling and dewatering during hydrostatic testing, routing batching and product removal operations in pipeline. Batch pigs equip with gauging plate are used to check pipeline roundness, prevention of debris and also ensure excessive weld penetration. Prior to intelligent pig they are used to prove minimum bend radius. The main function of this pig is to prevent contamination of transport products.

There are at least three sources that create contamination in product pipeline, which are; flow regime, pipeline design and operational procedure (Williamson, 2015)

Figure 2.1: Batching pig

2.2.2 Gauging pig

Pig can be configured for gauge purpose this is achieved by incorporating a gauge plate to the pig. The gauge plates are made of aluminum or steel. The plates are available in variety of thickness. Gauge plate fitted on batch pigs are used to prove pipe roundness and also indicate obstructions or internal damage to pipeline. By inspection of the baseplate, any major damage to the gauge plate indicates obstruction in the internal of the pipeline (Li et al., 2012). It is important to observe that the process of gauge pig travelling through the pipeline, collision can occurs at locations where no deformations are present such as elbows (Li et al., 2012).

Figure 2.2: Gauging pig

2.2.3 Cleaning Pig

The cleaning pig is one of the most important types of pigs used in the industry. Configuring pigs for cleaning involve the incorporation of circular brushes, spring-mounted bushes, scrapers, or plough blades for waxes and sludge or more aggressive tools such as carbide ‘pins’ for removal of scales. Other functions are corrosion control and dewatering. The cleaning pig has many functions, which are called into play during different phase of pipeline life cycles.

During construction phase of pipeline, pigs are used to remove construction debris or dirt that is left inside the pipe.

After construction, in the hydro testing process, pig is pumped through pipeline with water, as a method to remove trapped air inside the pipeline. After which a cleaning pig is used to evacuate the water and dry the pipeline before it is ready for commissioning.

Cleaning pig is also very important during the operational life of the pipeline. It is used to remove substances that have the tendency to obstruct flow within the pipeline, or can damage the pipeline itself, while flow inside pipeline is not obstructed. The action of debris removal, the cleaning pig ensures that pipeline maintains its maximum efficiency (Williamson, 2015).

Cleaning pigs can be light or heavy in weight; this is because of the different functions of the pig and the different types of pipeline configuration. Figure 2.3: Cleaning pig the cleaning pig use in the pre-commissioning operation of 12m test rig in IK AS facility in Forus, Stavanger.

Figure 2.3: Cleaning pig

2.2.4 Magnetic Pig

These types of pigs are fitted with powerful magnets on the circumference of the pig mandrel. The magnet removes ferrous debris such as welding rods, electrodes, metallic construction debris, corrosion product and other magnetic debris in the pipeline. This type of pig can also provide activating pig signalers as secondary function. Magnetic pig has been advanced to accurate determination of the size of corrosion defects. This is important in determining defect severity (Nestleroth et al., 1996).

Figure 2.4: Magnetic pig

2.2.5 Foam Pig

Foam pigs also allow the addition of gauge plates, brushes, abrasives etc., to either be fitted into the pig using bolts, or by direct casting into the polyurethane coating.

They are available in different shapes. It can be bullet shaped, have concave ends or flat ends, be jelly coated on the outside or sometimes have a silicone carbine coating. In addition, some foam pigs can have a crisscross pattern with silicone carbine implanted in the pig.

Coated foam pigs are used for general cleaning, whereas the more abrasive coating of silicone carbine is used for cleaning lines with build-up. The crisscross pattern is also used for medium-length runs in pipe where extra abrasion resistance is required.

Foam pigs are flexible, enabling them to compress and expand so that they can travel through multi-diameter pipelines and navigate bends in the pipeline.

Light-density foam pigs are used to pass through the pipeline first because their open-cell foam aids the drying of pipelines after hydrostatic testing. Medium-to-heavy density foam pigs are used during pipe construction, start-up, during operations, for maintenance and emergencies

Solid polyurethane pigs are used majorly in batching or displacement of fluid in petroleum, chemical or process pipelines.

The shape of the pig dictates how fast it travels while in the pipe. The travel speed in turn determines the force of the pig's cleaning edge, with higher speed pigs being able to remove tougher debris.

In complex situation, where the diameter of pipeline changes along it routes, presence of x-mas trees and manifold, the conventional pig are not applicable, but the foam pig can be used due to its physical characteristics which are (Lima and Alves, 1995); density, tensile strength, wear resistance, tearing resistance, resilience, elasticity modules.

Figure 2.5: Foam pig

2.2.6 Intelligent Pigs

In a broad sense, these type of pigs are cost effective way of determining the true integrity of pipeline system (Hodgman, 1996). They are special type of pig design with powerful technology. These types of pigs are design to carryout complex task other than the normal task. They provide information on the condition of the pipe and/or its contents. The tasks involve data logging as they travel through the pipeline. Mapping, geometry measurement, crack detection, measurement of metal loss, others are;

- Temperature and pressure recording
- Wax deposition measurement
- Bend measurement
- Product sampling
- Leak detection
- Photographic inspection
- Corrosion detection, etc.

Figure 2.6: Intelligent Pig

2.2.7 Gel Pig

The principal part of this pig is the gel. The gel pig is chemically constructed with semi-rigid or rigid structure. The gel is formed by gelling various medium (water, glycol, methanol, solvent, diesel, and crude). Because of its structure the gel pigs are used where mechanical (Conventional) pigging is almost impossible. Some of the constraint that warrant the use of the gel pigs are tight bends, changes in the internal diameter, or lack of launching or receiving hardware.

The benefit of using the gel pig during pipeline pigging are; reduce wear of pigs, decrease fluid bypass, increase drive efficiency and improved capacity to carry load.

The gel pig is efficient in debris removal, dewatering, swabbing, de-oiling, flooding, fluid separation, recovery of mechanical pigs and contact treatment.

Some type of gels are limited in that they are not suitable for long runs, in dry pipeline or pipeline where the driving medium is gas as a result of bypass. Gel pigs are frequently used during initial commissioning or at period of continuous maintenance.

In general the principal advantages of gel pigs, they can perform most of the functions of conventional pigs, and also with additional chemical capabilities and also can be injected into pipeline through a 2-inches valve (Uzu et al., 2000).

2.2.8 Sphere Pigs

Sphere pig are mostly solid in shape, others are inflated with air, water and glycol. This type of pig is the best or prefers choice of pig for removing liquids from gas lines. It makes use of the launching system. During cleaning, series of sphere are loaded into the automatic launcher at a predetermined frequency. At the receiving end, spheres are captured in a trap. Pipelines are design for the use of sphere or pigs, but not for both. Systems designed for launching and recovery of sphere may require modification of launchers and receivers before conventional pigs can be used (Williamson, 2015).

Figure 2.7: Sphere pig

2.3 Pig selection

Pig selection depends on several factors, these include pipeline type, material, length, and fluid type (purity of material being transported), propelling medium and the function to be performed (Pharris, 2007). In-addition to pipeline characteristic, which are;

- The minimum and maximum internal line
- Maximum distance pig must travel
- Minimum bend radius, and bend angles

Other features are such as valve types, branch connections, and the elevation profile.

2.4 Pigging functions

The function of pig will warrant the type of pig selected. There are various functions of pigs, they are classified into; fluid separation, displacement and cleaning and internal inspection (Williamson, 2015).

2.4.1 Fluid separation

Pigs are used as a solid barrier between different fluids, e.g. liquid and gas. With this characteristic of pig, it can be used in a train to ‘batch’ different fluids or chemicals. This is shown by the pig below. Figure 2.8: Fluid separation pig, Slug fresh water, slug glycol and nitrogen gas are separated, prevented from mixing with each other by pigs.

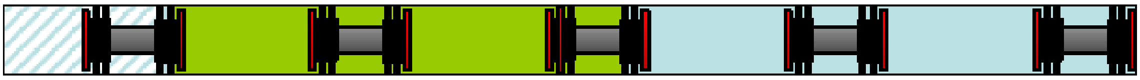


Figure 2.8: Fluid separation pig

2.4.2 Displacement

Fluid in between the solid interface between the pipeline wall and the pig sealing element are transported along in the pig direction of movement. Although the sealing is not perfect, this result to some bypass due to the internal pipe roughness, weld penetration and seal bypass. During construction, air within pipeline is displaced with water, the water is displaced with air and the pipe dried, the dry air is displaced with nitrogen or the main product to be transported.

2.4.3 Cleaning

Pipelines are cleaned to enhance the flow rate and control corrosion. The cleaning action of the pig is made possible by the sealing element of the pig and also the direction of flow of the fluid. This cleaning is further enhanced by the incorporation of brushes, scrapers or other aggressive tools to the pig. In some cases magnet is added to pick up ferrous debris from pipeline. Turbulence within the fluid aids the suspension and cleaning of small debris in addition to the bypass port through the pig or the pipeline wall. For waxes and sludges cleaning, it is effectively done by the aid of brushes and scrapers incorporated to the pig.

2.4.4 Inspection

Pigs are used for internal inspection. These pigs are also referred to as smart or intelligent pigs. Most pipeline operator implements integrity Management Plan. This plan incorporates the use of internal inspection pigs. These pigs come in varieties of shapes and sizes with each providing data which detects dents, buckles, metal loss and cracking.

2.5 Reasons for pigging

Pigging of a pipeline is required at various stages of a pipeline's life for a variety of reasons. Pipeline life cycle with regards to pigging can be classified into four; these are pre-commissioning, commissioning, operation and decommissioning

2.5.1 Pre-commissioning pigging

Pre-commissioning covers the process of preparing new laid pipeline for operation. Pipeline pigging has a major role to play in order that the line meet the required specification. New pipelines built need to be cleaned from construction debris and prepared for hydrostatic testing. Pig train for cleaning, gauging, and batching pigs to flood the line are general used. Finally the line is pressure tested and then followed by dewatering and drying in the preparation service. For subsea lines, the dewatering and drying of the line are sometimes delayed for several month (David Russell, 2005).

2.5.2 Commissioning pigging

On commissioning of new pipeline, the product introduces into the line, a batch pig or pigs are used to separate the product from the current medium in the pipeline. Also for a new line, the existing operational trunkline is positively isolated, de-oiled and flushed clean using foam pigs driven in water.

2.5.3 Operational pigging

Operational pigging removes water, wax, condensate, scale and other debris which are formed during the operation of the pipeline while transporting crude oil and gas. It also serves the purpose of product separation and application of inhibitor (Combe and Hair, 2011). It is paramount that the integrity of the pipeline is maintained. Operational pigging is the effective and cheap way of maintaining the life of pipeline. This will maintain flow, minimize back flow. (Combe and Hair, 2011)

2.5.4 Decommissioning pigging

New pipelines lifespan are thirty years and over in most cases. Before the excavation for construction of the new pipeline, old pipeline are cleaned and flushed using foam pigs and water to ensure that no oil, grease or other hydrocarbon are present in the line during excavation and cutting (Creek, 2004). This process is also done when pipeline usage is changed in addition to chemical and mechanical means to get rid of the old transporting fluid.

3. Polyurethane

3.1 Introduction

The development of elastic polyurethane began as a program to find a substitute for rubber during the World War II, which at that time, rubber was expensive and hard to obtain (Prisacariu, 2011). In the year 1950 Bayer et al sequentially studied the formulations that led to the advent of the Vulkolland rubbers (Clemitson, 2015). These polyurethane elastomers showed many advantages over natural rubber in that they had higher abrasion resistance and tear strength, better resistance to oxygen ageing while displaying a good flexibility and elasticity. This was not achieve but until the discovery of the preparation diisocyanates which is a chief constituent in the formation of polyurethane

The use of the polyaddition principle to produce polyurethanes from liquid diisocyanates and liquid polyether or polyester diols opened new field of study, especially when compared to already existing plastic obtained by polymerization olefins, or by polycondensation (Prisacariu, 2011).

3.2 Polyurethane Raw Materials

Polyurethane is a body of polymer in which molecular chain segments are bound together with urethane linkages (Saidpour et al., 2008). Polyurethane are made from raw material, which are: polyols, isocyanates, water, methylene chloride, catalyst, chain extenders, colourants, air and additives (e.g., fire retardants, antioxidants, ultraviolet (UV) protectors) (Defonseka, 2013). These raw materials are combined on 'systems' rather than a straightforward formula, and are formulated to achieve predetermined properties to suit end applications (Aglan et al., 2008). Some of the most important properties of polyurethane are density, stiffness, heat or fire resistance. The formulae of the system using these raw material are designed around its properties or in another words in usage. The precise constituent of shore grade 65, 75 and 85 can be seen in Appendix 1.

Polyurethane characteristics are controlled by their molecule structures and it’s include degrees of flexibility/rigidity, density, cellular structure, hydrophilicity or hydrophobicity, processing characteristics, and end–used property (Szycher, 2012). The plastic nature controls the processing characteristics. Which determine whether the material is thermoplastic (linear molecule structure) or thermoset (cross- linked molecular structure). In general PU are structured with hard and soft segments which allow for microphase separation between the two. The hard segment blocks acts as thermally reversible cross-links and affect the stiffness (storage modulus), tensile strength, and tear strength. The soft segments allow soft domains, which give the material its elastic properties and low temperature resistance (Aglan et al., 2008). This unique properties gives PU group its high flexibility in formulations. In summary the general principle of the structure property relationship are (Szycher, 2012).

- Molecular weight - Properties like tensile strength, melting point, elongation, elasticity, glass transition temperature etc. increase up to limiting value and remain constant with increase in molecular weight
- Intermolecular forces - Temperature and stress affect the weak bond. Examples of weak bonds are hydrogen bonding, polarizability, and van der waals forces. In addition chemical bond is also affected. Also in cases where there are repulsion between like charges or bulky chains, or if there is high cross density, the effect of intermolecular forces is reduced
- Stiffness chain - Aromatic rings stiffen the polymer chain and result to high melting point, hardness, and decrease in elasticity. Presence of flexible bonds favours softness, low melting point, and elasticity and low glass transition temperature.
- Crystallization - Crystallization is favoured by linearity and close fit of polymer chains. This leads to reduction in solubility elasticity, elongation, flexibility and increase in tensile strength, melting point and hardness.
- Cross linking - Increase in cross-linking results to increase in rigidity, softening point, and modulus of elasticity. In addition it results to elongation and swelling of solvent.

In the formation of polyurethane at room temperature and up to 50 °C, isocyanates react with hydroxyl group to produce polyurethane, while with amines and /or water they will produce urea linkage. At a higher temperature up to 150 °C, further reaction produce allophanate, biuret and isocyante linkages (Szycher, 2012).

Polyurethane can be considered as mixed amide esters of carbamic acid, and thus their properties are between polyesters and polyamides.

When linear polyurethane is desired, lowest temperature is required in the reaction, and higher temperature is used when high cross-linking and branching through secondary reaction is desired. At temperatures above 250 °C, all polyurethane starts decomposing (Szycher, 2012). In decomposing polyurethane yields free isocyanates, alcohols, free amines, olefins, and carbon dioxide (Lyman, 1960).

3.2.1 Polyols

Polyols is one of the most commonly used ingredients in the formation of polyurethane. These are long-chain alcohols that are made by polymerising common hydrocarbon oxides. This results in linkages that connect the hydrocarbon portions of the chain and hydroxyl functional groups at the end of the chain. Water and traces of alcohol act as co-initiators to produce some diols and monols, so the overall functionality of the polyol is between 2 and 3. Polyols with slightly higher functionalities are also available commercially.

Several properties of polyurethane are controlled by varying the functionality of a polyol. For example, increasing the polyol functionality without changing the molecular weight produces a slight increase in polyurethane hardness and a small reduction in tensile strength, tear strength and elongation (Defonseka, 2013). In addition, as functionality increases, the time at which the gel point occurs decreases. Increasing the equivalent weight of the polyol (molecular weight divided by the functionality) while maintaining the functionality of a polyol produces a polyurethane with increased tensile strength and elongation. However, the increased equivalent weight also reduces the reactivity of the polyol.

Polyol with low molecular weight, creates hard plastics, and high molecular weight creates flexible elastomers. The reactivities are not same for all hydroxyl groups. Primary alcohols react readily at 25-50 °C, Secondary and tertiary alcohols are about 0.3 and 0.005 times less reactive than the primary ones.

Altering the level and distribution of ethylene oxide in the molecular chain can have a dramatic effect on the reactivity, emulsifying capacity and affinity for water of the polyether. For example, a high level of ethylene oxide in the recipe will increase the reactivity of the polyol. If the ethylene oxide is added stepwise rather than as a mixture of oxides, a block polyol is formed rather than a random polyol. If the resulting ethylene oxide block is at the end of the polyol chain, reactivity will be increased even further because the terminal hydroxyl groups form reactive primary alcohol. As the level of ethylene oxide within the polyol increases, the hydrophilicity (affinity for water) and emulsifying capacity also increase.

Polyols are liquids and are available commercially in drums or in tanker when large quantities are required by manufacturer. Their shelf-life is six months and for optimum yield should be kept at room temperature <25 °C and should be stirred before use (Defonseka, 2013). During storage time, precautions should be taken to prevent water absorption, especially from the atmosphere.

Polyethers, polyesters and hydrocarbon families can also serve as polyols for the manufacture of polyurethane. Also bio-polyols has come upstream as a replacement for polyols due to its environmental friendliness (Szycher, 2012).

3.2.1.1 Polyethers

Poly (oxypropylene) glycol is the most common polyether polyol, it is made by ailkaline polymerization of propylene oxide. It is low in cost and also provides good flexibility.

Polytetra methylene ether glycol (PTMEG) is frequently used for higher strength. It also called poly (oxytetramethylene) glycol. PTMEG is made by acid polymerization of tetrahydrofuran. Toughness, resiliency, high abrasion resistance, inherent hydrolysis resistance, and superior low-temperatures properties are the characteristic of polyurethane made from PTMEG, when compared to polyether – based polyols (Szycher, 2012).

3.2.1.2 Polyesters

These polyols are used to provide high strength to polyurethane elastomer. Poly (ethylene adipate) is an example of linear aliphatic polyester. The concentration of ester groups on the polyester determines the thermal behavior of polyester-based urethanes. Increase in the ester group concentration leads to reduced flexibility at low temperature, high hardness, high modulus and increase in permanent elongation. Reduction of ester group concentration improves the low-temperature flexibility and reduces the tear strength.

3.2.1.3 Hydrocarbons

Hydrocarbon polyols are synthesized in structures such as hydroxyl-terminated polybutadiene glycols, this result to lower polarity, better electrical insulation, and higher resistance to hydrolysis (Szycher, 2012).

Trihydroxyl polyols or triols are polyols with three hydroxyl groups, which are glycerine. Cross-linked polyurethane are formed when triols react with isocyanate. The stiffness of the polymer depends on the number of cross-linking. If rigidity of polyurethane is required, the polymer structure is highly linked, for flexibility of polyurethane, less cross-linking is needed. Branching and cross-linking are most commonly accomplished by the use of higher – functionality polyols.

3.2.2 Bio-polyols

Earlier polyols originated from petroleum byproducts. Due to global environment issues the need for alternative sources has led to bio-polyols. Bio-polyols are made from vegetable oils such as soya, canola and peanut oil (Defonseka, 2013). Bio-based material are used chiefly for polyurethane production.

Bio-polyols are clear liquids, ranging from colourless to slight yellow. Their viscosities vary and are a function of their molecular weight and the average number of the hydroxyl molecules.

The rise of cost of petroleum feedstock and the enhanced global desire for environmental friendly product have created the vacuum for the demand of bio-polyols as a replacement for polyols which are mainly bye-product of petroleum.

3.2.3 Isocyanates

Isocyanates is one of the most important component in the production of polyurethane. The most common manufactured isocyanate is toluene di-isocyanate (TDI) and methylene bisdiphenylisocyanate (MDI), plus higher oligomers for increased functionality and cross-linking. Other forms of isocyanates that are used are diphenylmethane di-isocyanate, mixtures of 2,4 –TDI and 2,6-TDI. The TDI are low in cost and high in quality that are used in the production of polyurethane. The use of blend of TDI isomer improves the polyurethane formed.

The PU hard segment are either aliphatic or aromatic. The aromatic isocyanates are more reactive than the aliphatic diisocyanates, aliphatic isocyanates are stable and light (Frisch, 1972).

The reaction between linear–chain polyol, diisocyanate and a low molecular weight chain extender lead to the production of elastomer. Elastomer properties depends mainly on the chain structure, the degree of branching of the polymeric intermediate and the stoichiometric balance of the components.

The chemical structure determines the reactivity of the isocyanates. Aromatic isocyanates are generally more reactive than the aliphatic ones.

The presence of electron-withdrawing substituents on the isocyanate molecule increases the partial positive charges on the isocyanate carbon and moves the negative charge farther away from the site of reaction. This leads to the transfer of the electron from the donor substance to the carbon easier, thus causing a faster reaction. On the other hand, the presence of electron donating substituents on the isocyanate compounds can cause slower reactions

3.2.3.1 Prepolymers

Prepolymers are the reaction product of polyol or blend of polyols with excess isocyanate. There are different method of arriving at the product. One is mixing all the reactant at once, this method is the fastest economical and simple. Other methods involve two-steps or three-steps processes. These processes help in greater control of toxicity, reactivity, structure and properties process. Prepolymers are made by slow addition of polyol or blends of polyols to the isocyanate at a controlled temperature of 15-22 °C, followed by reaction to constant free isocyanate content in addition to catalyst (Szycher, 2012).

3.2.4 Chain Extenders and cross-Linkage

These are low molecular weight hydroxyl and amine terminated compound that assist in the polymer shaping or forming of the polyurethane. The three most common additives for stepwise extension are 1, 4-butane-diol, water and diamines. The functionality and the stoichiometry of the additives determine whether it is chain-extender and/or cross linking agents.

Chain extender structure has strong influence on PU mechanical performance. Modifying the ratio between the polyol and the chain extender result in PU that changes from hard, brittle material to rubbery elastomer as a result of the variation of mass ratio of the non-polyol components to the total mass of the polymer (Hepburn, 2012).

3.2.4.1 1ndigenous and cross-Linkage

Apart from high functionality polyols, and/or polyamines, there are many other reactions which can contribute significant cross linking during polymerization and cure of polyurethane. These are; allophanate, biuret, and isocyanurates (Szycher, 2012).

3.2.4.2 Allophanate

Polyurethane that is formed in the presence of excess polyisocyanate, the urethane group can supply an active hydrogen to react with isocyanate, thus forming a branch point. Also a diisocyanate could form similar cross-link between two polyurethane chains. These cross-links are not stable as the conventional cross-links formed from polyfunctional polyols and polyisocyanates; they are thermally liable and open quite easily at high temperature.

3.2.4.3 Biuret

Polyurea formed in the presence of excess polyisocyanate, the urea group can supply active hydrogens to react with the isocyanate and a branch point is formed. Diisocyanate can also form a cross-link between two polymer chains. These cross-links form more readily than allophanates and are somewhat stabler than allophates, but they are still thermally labile and open fairly easily at higher temperatures (Szycher, 1991).

3.2.4.4 Isocyanurate

Under proper conditions, excess isocyanate forms cyclic trimers which are isocyanurates.

In the advent of diisocyanate or higher polyisocyante are used as isocyanate, isocyanurate rings acts an extremely stable cross-links in the formulation of polyurethane. High heat stability and flame retardation properties are the characteristic of polyurethane formed with this process (Szycher, 2012).

3.2.4.5 Block Copolymers

When small comonomer units are assembled randomly into polyurethane molecule, the resulting random copolymer has an overall average structure that is fairly uniform and forms a single homogeneous phase containing this average composition and structure (Noshay and McGrath, 1977). When the growth of a copolymer molecule produces fairly large area of one monomer structure alternating with fairly large areas or another monomer structure.

In polyurethane, polyol forms fairly large block even before they are reacted with the isocyanate. Thus, polyurethane are block copolymers. The separation of these block into domain has a major synergistic effect on the properties of the resultant polymer (Szycher, 1991).

3.2.4.6 Heterblock Copolymers

The stepwise synthesis of polyurethanes, with active hydroxyl, amine, and/or isocyanate end-groups remaining after each intermediate step, provides the organic polymer with the additional possibility of combining these polyurethane blocks with blocks of other polymer structures, to combine the best properties of polyurethane with the best properties of the other polymer as well.

3.2.5 Catalyst

Catalyst is used in the production of polyurethane. Catalyst greatly influence the reactions, in terms of initial reactants, reaction rate and direction of polymer-forming process (Hepburn, 2012). Two reactions that take place, one the polymerization reaction. Polyfunctional isocyanates react with polyols to form polyurethane. In the gas-producing reaction also known as blowing reaction, isocyanate reacts with water to form polyuria and carbon dioxide. The reaction rates are different, both reaction are temperature, catalyst level, catalyst type and other factor dependent. Quality polyurethane requires both reactions must be controlled and balanced.

If the gas-producing reaction occurs faster than the polymerisation reaction (gelling), the gas generated by the reaction may expand before the polymer is strong enough to contain it, and this may result to collapse of polyurethane. In contrast, if the polymerisation occurs faster than the gas-producing reaction, the polyurethane shrinks. If these two reactions are balanced appropriately, uniform open cells will dominate the polyurethane structure.

The catalysts mostly commercially used in polyurethane process are tertiary amines and organic tin compounds(Hepburn, 2012).

Tin catalysts strongly catalyse the polymerisation reaction. Polyols and formulations that permit a range of tin levels to be used without causing processing problems are desirable. Insufficient catalyst will lead to PU splits or possibly collapse if the polymer fails to gel sufficiently. Excessive catalyst will cause closed cells and shrinkages (Defonseka, 2013).

In contrast to tin catalysts, tertiary amines catalyse the gas-producing reaction. The residual catalyst escapes from the finished PU after production or is incorporated into the polymer structure. The various tertiary amines in use differ greatly with regard to catalytic activity and efficiency, so overall reaction rates can be optimized by using mixed catalyst systems. Although amines and tin compounds catalyse different reactions within the PU sequence, they do not act entirely independently. Typically, each catalyst influences both reactions in the PU process, and the ability of PU chemist to maintain an appropriate balance between the two PU reactions can be greatly influenced by the composition and selection of specific catalysts (Defonseka, 2013).

3.2.6 Blowing Agent

The most common blowing agent used in polyurethane building structure are water and methylene chloride. There are other forms of blowing agent which are not in used because of it hazardous effect with the environment. Predominantly the methylene chloride is use. Although water is used, it is not present in most polyurethane. Water reacts with isocyanate to form compounds which remain in the polyurethane and also carbon dioxide, which acts as a blowing agent. Auxiliary carbon dioxide can also be added as liquid to augment the blowing portion of the polyurethane reaction (Defonseka, 2013).

3.2.7 Surfactants

One of the main function of surfactants is the prevention of coalescence of rapid growing cells until they have attained sufficient strength through polymerization to become self-supporting. Different surfactant are available and are designed to meet specific needs in the production of polyurethane. The most common type of surfactant used is the silicone surfactant. This surfactant serves the following functions (Defonseka, 2013):

- It provides control of cell size through the promotion of homogenous fine cells
- It reduces the surface tension for improved chemical affinity with polyol
- It provides film resilience known as self –healing in the bubbles.
- It counteracts the deforming effect of any solids added to the reacting system.
- Reduction of surface tension for improved chemical affinity with polyol.

3.2.8 Methylene Chloride

Methylene Chloride is used in the production of polyurethane. It aid in the attainment of densities and softness not obtainable by the use of conventional blowing agent; water. Methylene chloride is liquid with low boiling point.

Methylene chloride serves as auxiliary blowing agent by complementing the flowing effects of carbon dioxide generated from water –TDI reaction. In addition, methylene chloride acts as heat sink.

3.2.9 Additives

Additives are material added into polyurethane production in order to achieve specific or the desired property set out on the onset. Additives does not interfere with the polyurethane chemistry. Most additives are derived from naturally occurring vegetable, animal, or mineral substances. For additives to be useful, it must hold material together and also withstand operational loads and last the life of the product (Harper, 2004). Examples of common additives are; pigments, fillers, flame retardants, antioxidants, cell opener, plasticisers, anti-bacterial agents, colourants, crosslinkers.

3.3 Description of Polyurethane Process

The substructure of polyurethane contains many atoms and functional groups. Examples of these functional group and atoms are aliphatic, aromatic, carbonates, ether, ester, hydroxyl, urethane, amine, urea, biuret, isocyanate, and isocyanurate groups. They contribute individually to the end property of the polyurethane. The structure of PU elastomer are influenced by intermolecular forces such as hydrogen bonding, polarizability, van de waals forces, stiffness of the chain and cross linking (Shanks and Kong, 2013).

Polyurethane elastomer are prepared in two main process. The first way, which is the simplest and the most used method, it involves mixing a liquid diol, a polyol and diisocyanate and to cast the mixture in a mold while still liquid. The curing of the cast mixture will yield elastomer product.

Thermoplastic elastomer is produced when the reactant chosen such that they produce a linear structure. This is referred to as one shot process.

The other method is the reaction of linear hydroxyl-terminated polymer with an excess of diisocyanate to form an isocyanaterminated polyer called prepolymer. The prepolymer is either a viscous liquid or a low-melting solid.

The next step is chain extension and network formation with a small-molecule-weight polyol or amine called chain extender. If the NCO/OH (ratio of isocyanate and polyol) ratio is greater than 1, then this step is usually accompanied by some allophanate and/or branch point formation.

Cross-linking development in elastomer depends on the reaction of some isocyanate groups to form biuret cross-links. A more useful procedure is used with a least one component having more than two reactive end groups to obtain the required amount of cross-linking.

The properties of elastomers are determined mainly by the chain structure, the degree of branching of the polymeric intermediate, and stoichiometric balance of the components. The ratio of NCO to OH for optimum strength is usually 1.0-1.1. As the ratio falls below 1.0 the mechanical strength, hardness and resilience decreases and elongation and compression increases very sharply.

3.4 Mechanical Property of Polyurethane

Shore A and shore D of elastomeric material are characterized by the following mechanical properties:

- High tensile strength and outstanding resistance to tear propagation
- High wear and abrasion resistance

- Excellent damping characteristic
- Very good low – temperature flexibility
- High resistance to oil, greases, oxygen and ozones

These mechanical properties make PU a suitable choice for sealing and cleaning purposes. Hence it is one of the most used material for pig design.

4. Plate theory

4.1 Introduction

A plate is a flat structural element, and is considered thin when its thickness is small in magnitude when compared to its span or its diameter. The thickness is often constant, although it may varies and is usually measured normal to the middle surface of the plate. 4.1 shows an arbitary plate.

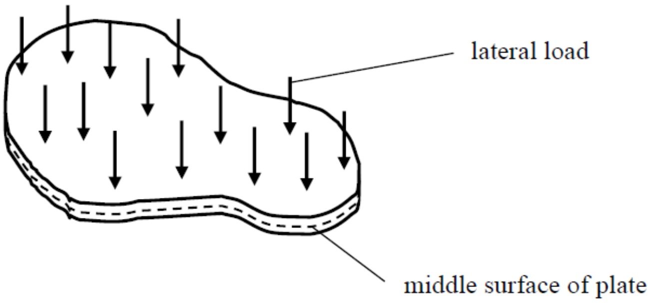


Figure 4.1: Plate

4.2 Plate Theory

Two dimensional plane stress theory is used to solve plate subjected to in-plane loading only. In addition, plate theory covers mainly lateral loading. In plate theory, the stress components varies throughout the thickness of the plate, so that bending moment is allowed. This is one of the differences between plate theory and plane stress. See Figure 4.2

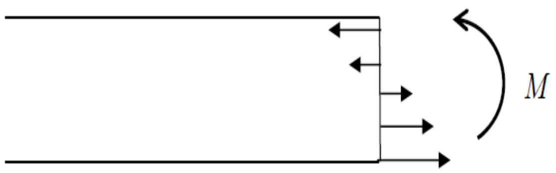


Figure 4.2: Stress distribution through the thickness of plate and resultant bending moment

In plate theory, assumptions are taken into consideration and the three dimensional equations of elasticity are used. This point to the fact that plate theory is an approximate theory. It is similar to the beam theory, only that is attracts an extra dimension into it.

The plate theory is an accurate theory provided the plate is thin when compared to other dimensions. Also the deflections are small when compared to its thickness. The plate can be more complicated when compared to the beams. This is as a result that the plate can be subjected not only to bends, but in-addition torsion may occur, in another word, twist, as shown in Figure 4.3

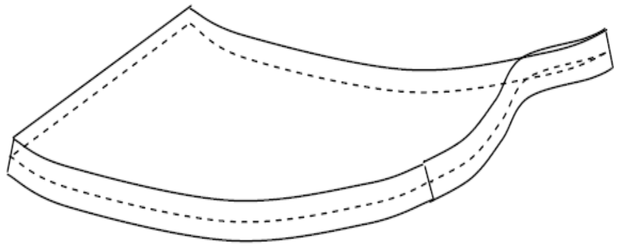


Figure 4.3: Torsion of plate

4.2.1 Assumptions of Plate Theory

Let the plate mid-surface lie in the x - y plane and the z – axis be along the thickness direction, forming a right handed set, as shown in Figure 4.4

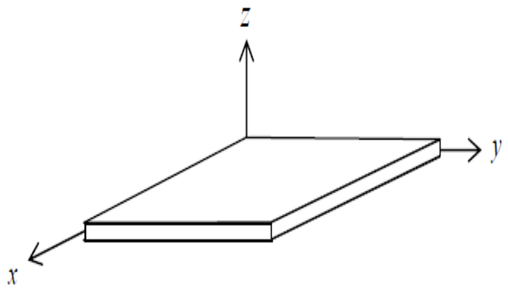


Figure 4.4: Cartesian axes

The stress components acting on a 3D typical element of the plate are shown in Figure 4.5

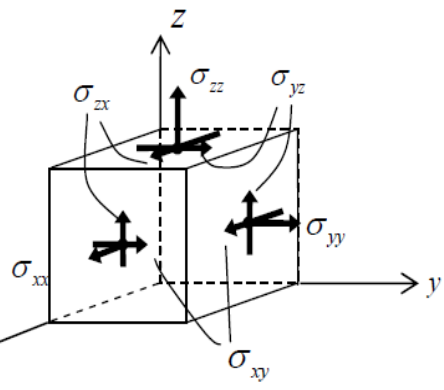


Figure 4.5: 3D stresses acting on a material element

The following assumptions are made;

(a) The mid-plane is a "neutral plane"

The middle plane of the plate remains free of in-plane stress/strain. Bending of the plate will cause material above and below this mid-plane to deform in-plane. The mid-plane plays the same role in plate theory as the neutral axis does in the beam theory.

(b) Line elements remain normal to the mid-plane

Line elements lying perpendicular to the middle surface of the plate remain perpendicular to the middle surface during deformation, Figure 4.6; this is similar the "plane sections remain plane" assumption of the beam theory.

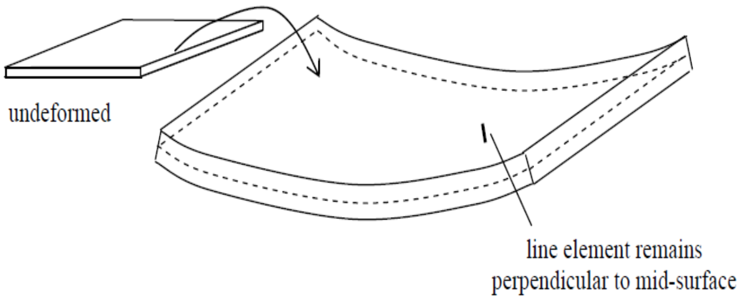


Figure 4.6: Deformed line elements remain perpendicular to the mid-plane

(c) Stress vertical to the plate is assumed zero

Line elements lying perpendicular to the mid-surface do not change length during deformation, so that $\sigma_{zz} = 0$ throughout the plate. Again, this is similar to an assumption of the beam theory. These three assumptions are the basis of the Classical Plate Theory or the Kirchhoff Plate Theory.

4.3 Classical Plate Equation

The small transverse (out-of-plane) displacement, w, of a thin plate is governed by the classical plate equation also known as the plate equation of Biharmonic type.

$$\nabla^4 w = \frac{p(x,y)}{D}$$

And $$D = E^* I^*$$

Also $$\nabla = \nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2} \quad \text{for circular plate}$$

Where

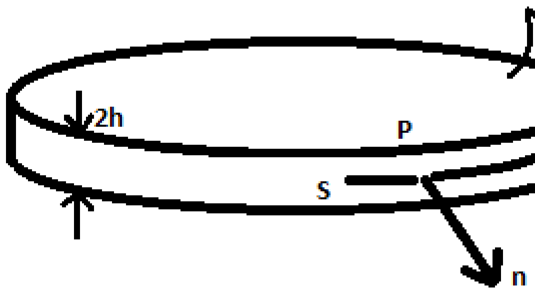
p - Distributed load (force per unit area)

w - Displacement

D - Bending/flexural rigidity of the plate

The plate equation of biharmonic type equation can be solve applying different boundary conditions, knowing the load, $p(x, y)$

4.3.1 Boundary condition of arbitrary plate shape



Where;

D - Flexural rigidity

n - Local normal

s - Local tangent at perimeter

For bending and twisting moment, generally we write,

$$M_x = -D(\frac{\partial^2 w}{\partial x^2} + \nu \frac{\partial^2 w}{\partial y^2})$$

In terms of n and s coordinates at P

$$M_n = -D(\frac{\partial^2 w}{\partial n^2} + \nu \frac{\partial^2 w}{\partial s^2})$$

$$M_{ns} = D(1 - \nu) \frac{\partial^2 w}{\partial n \partial s}$$

Shear force acting in z-direction at the edge at P

$$S_n = \frac{\partial M_n}{\partial n} - \frac{\partial M_{ns}}{\partial s}$$

$$S_n = -D\frac{\partial}{\partial n}(\frac{\partial^2 w}{\partial n^2} + \frac{\partial^2 w}{\partial s^2}) = -D\frac{\partial}{\partial n}\nabla^2 w$$

4.3.2 Types of Plate Boundary

The three main plate boundary conditions are namely; built-in-edges, simple support edge and free edge. For different boundary conditions, using

a) Built-in edge

Deflection and slope at the edge is zero

$$w = 0 \qquad \frac{\partial w}{\partial n} = 0$$

b) Simply supported edge

Simple supports do not prevent rotation; but deflection is zero

$$M_n = 0 \qquad w = 0$$

$$\frac{\partial^2 w}{\partial n^2} + \nu\frac{\partial^2 w}{\partial s^2} = 0$$

$$M_{ns} \rightarrow 0$$

c) Free edge

No moments or shear forces applied

$$\frac{\partial^2 w}{\partial n^2} + \nu\frac{\partial^2 w}{\partial s^2} = 0$$

$$\frac{\partial^2 w}{\partial n \partial s} = 0$$

$$\frac{\partial}{\partial n}\left(\frac{\partial^2 w}{\partial n^2} + \nu\frac{\partial^2 w}{\partial s^2}\right) = 0$$

4.3.3 Axis – Symmetric plate

The axis-symmetric cylindrical coordinates, if the stretching is regarded as negligible, the plate equation is polar cylindrical coordinates;

$$\nabla^4 w = \frac{p(x,y)}{D}$$

$$\nabla^4 = \nabla^2(\nabla^2) = \left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2}\right)\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2}\right)$$

Transformation r and x coincide

$$\frac{\partial^2}{\partial x^2} = \frac{\partial^2}{\partial r^2}$$

$$\frac{\partial^2}{\partial y^2} = \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2}$$

$$\frac{\partial^2}{\partial x \partial y} = \frac{1}{r}\frac{\partial^2}{\partial r \partial \theta} - \frac{1}{r^2}\frac{\partial^2}{\partial \theta}$$

All the equation becomes

$$M_r = -D\left[\frac{\partial^2 w}{\partial r^2} + \nu\left(\frac{1}{r}\frac{\partial w}{\partial r} + \frac{1}{r^2}\frac{\partial^2 w}{\partial \theta^2}\right)\right]$$

$$M_\theta = -D\left[\frac{\partial^2 w}{\partial r^2} + \nu\left(\frac{1}{r}\frac{\partial w}{\partial r} + \frac{1}{r^2}\frac{\partial^2 w}{\partial \theta^2}\right)\right]$$

$$M_{r\theta} = D(1-\nu)\left(\frac{1}{r}\frac{\partial^2 w}{\partial r \partial \theta} - \frac{1}{r}\frac{\partial w}{\partial r}\right)$$

$$S_r = -D\frac{\partial}{\partial r}(\nabla^2 w)$$

$$S_\theta = -\frac{D}{r}\frac{\partial}{\partial r}(\nabla^2 w)$$

If both geometry and loading is axis-symmetric

$$\frac{\partial}{\partial \theta} = 0$$

No variation with angular coordinate

$$\nabla^4 = \nabla^2(\nabla^2) = \left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r}\right)\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r}\right)$$

Which gives

$$\frac{1}{r}\frac{\partial}{\partial r}\left\{r\frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial w}{\partial r}\right)\right]\right\} = \frac{p(r)}{D}$$

The equation above is integrated directly using boundary conditions to find four integration constants.

With moments and shear forces

$$M_r = -D\left[\frac{\partial^2 w}{\partial r^2} + \frac{v}{r}\frac{\partial w}{\partial r}\right]$$

$$M_\theta = -D\left[\frac{1}{r}\frac{\partial w}{\partial r} + v\frac{\partial^2 w}{\partial r^2}\right]$$

$$M_{r\theta} = 0$$

$$S_r = -D\frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial w}{\partial r}\right)\right]$$

$$S_\theta = 0$$

All is valid for constant thickness, if thickness is variable, flexural rigidity is variable (function of r) since $h = h(z)$

Governing equation.

$$\frac{\partial}{\partial r^2}\left[D\left(\frac{\partial^2 w}{\partial r^2} + \frac{v}{r}\frac{\partial w}{\partial r}\right) + \frac{1}{r}\frac{d}{dr}\left(D\frac{1}{r}\frac{\partial w}{\partial r} + v\frac{\partial^2 w}{\partial r^2}\right)\right] = p(r)$$

Or since r is the only variable

$$\frac{\partial}{\partial r^2}\left[D\left(\frac{\partial^2 w}{\partial r^2} + \frac{v}{r}\frac{\partial w}{\partial r}\right) + \frac{1}{r}\frac{d}{dr}\left(D\frac{1}{r}\frac{\partial w}{\partial r} + v\frac{\partial^2 w}{\partial r^2}\right)\right] = p(r)$$

Some axi-symmetrical plates can be solved exactly by some stress function, ϕ approach

$$\nabla^4\phi = \nabla^2(\nabla^2\phi)$$

$$\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial z^2}$$

Stress components are;

$$\sigma_{rr} = \frac{\partial^2 \phi}{\partial z^2} + \frac{1}{r}\frac{\partial \phi}{\partial r}$$

$$\sigma_{\theta\theta} = \frac{\partial^2 \phi}{\partial r^2} + \frac{\partial \phi}{\partial z^2}$$

$$\sigma_{zz} = \frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r}\frac{\partial \phi}{\partial r}$$

$$\sigma_{rz} = -\frac{\partial^2 \phi}{\partial r \partial z}$$

4.4 Isotropic material

An isotropic material is same in all direction. None of the properties depend on the orientation; it is perfectly rotationally symmetric. Isotropic material must be homogeneous on the length scale of interest, i.e. the same at every point in the material. Example of isotropic material is rubber of which polyurethane falls into the class of material.

In general, the theory of stress is based on force and the associated force per area concept. Also the theory of strain is based on the concept of infinitesimal line of extensions and rotations between two infinitesimal lines. It is important that the stress at a point in a material to be related to the corresponding strain at that point, knowledge of material properties is required. These properties enter into the stress-strain temperature relations as material coefficients. The First Law of thermodynamic is the theoretical basis for these relation. The material properties are determined experimentally.

The first law of thermodynamic is the starting point in any relation of stress –strain and also that of temperature effect.

4.4.1 First Law of Thermodynamics

The stress-strain relationship depends on the material behaviour, isotropic material are treated mainly as material have the same properties in all directions. In addition the stress-strain relationship can also be derived from the first law of thermodynamics, which is also known as the law of conservation of energy. The total energy in a system is generally indeterminate.

The first law of thermodynamic states that, ‘the work performed on a system by external forces plus the heat that flows into the system from the outside equals the increase in the internal energy plus the increase in kinetic’ energy.

Mathematically the first law of thermodynamic can be represented by the equation below;

$$\delta W + \delta H = \delta U + \delta K$$

Where;

δW - Work performed on the system

δH - Heat that flows through the system

δU - Increase in internal energy

δK - Increase in kinetic energy

4.4.2 Isotropic and Homogeneous Materials

If the constituents of a material of are distributed sufficiently randomly, any part of the member will display the same material property in all direction, hence elastic ball bounce almost the same in all directions. A solid is said to be isotropic if its member is composed of randomly oriented constituents. A material said to be isotropic means it physical properties at a point are invariant under a rotation axes. Also, a material is said to be elastically isotropic if its characteristic elastic coefficients are invariant under any rotation of coordinates.

Homogeneous material properties are identical for every point in a member. In other words, the physical properties of the member are invariant under translation. Conversely, nonhomogeneous material properties change from one point to another.

For an Elastic isotropic materials, the strain energy density depends only on the principal strains.

4.4.3 Strain-Energy Density of Isotropic Elastic Materials

The strain energy density of an elastic isotropic material depends only on the principal strains ($\varepsilon_1, \varepsilon_2, \varepsilon_3$). If elasticity is linear, the strain energy density is given by;

$$U_0 = \frac{1}{2}\lambda(\varepsilon_1 + \varepsilon_2 + \varepsilon_3) + G(\varepsilon_1{}^2 + \varepsilon_2{}^2 + \varepsilon_3{}^2)$$

Where;

$\varepsilon_1, \varepsilon_2, \varepsilon_3$- Principal strains

λ, G - Lame’s elastic coefficient

In terms of stress, the strain energy density Uo is given by;

$$U_0 = \frac{1}{2E}\left[\sigma_{xx}{}^2 + \sigma_{yy}{}^2 + \sigma_{zz}{}^2 - 2v\left(\sigma_{xx}\sigma_{yy} + \sigma_{xx}\sigma_{zz} + \sigma_{yy}\sigma_{zz}\right)\right]$$

4.4.4 Thermoelasticity for isotropic materials.

Elastic isotropic material expand if their temperature rises and, to a first approximation the expansion is proportional to the temperature change. If the expansion is unrestrained, all dimensions will expand equally.

In terms of strain, the strain energy density $\mathbf{U_0}$ is given by;

$$U_0 = \frac{1}{2}\lambda\left(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}\right)^2 + G(\varepsilon_{xx}{}^2 + \varepsilon_{yy}{}^2 + \varepsilon_{zz}{}^2 + 2\varepsilon_{xy}{}^2 + 2\varepsilon_{xz}{}^2 + 2\varepsilon_{yz}{}^2) - c\left(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}\right)\Delta T + \frac{3}{2}c\alpha(\Delta T)^2$$

Where

$$\varepsilon_{xx} = \frac{1}{E}\left[\sigma_{xx} - v(\sigma_{yy} + \sigma_{zz})\right] + \alpha\Delta T$$

$$\varepsilon_{yy} = \frac{1}{E}\left[\sigma_{yy} - v(\sigma_{xx} + \sigma_{zz})\right] + \alpha\Delta T$$

$$\varepsilon_{zz} = \frac{1}{E}\left[\sigma_{zz} - v(\sigma_{xx} + \sigma_{yy})\right] + \alpha\Delta T$$

$$\varepsilon_{xy} = \frac{(1+v)}{E}\sigma_{xy} \quad \varepsilon_{xz} = \frac{(1+v)}{E}\sigma_{xz} \quad \varepsilon_{yz} = \frac{(1+v)}{E}\sigma_{yz}$$

And in terms of stress the strain energy density $\mathbf{U_0}$ is given by

$$U_0 = \frac{1}{2E}\left[\sigma_{xx}{}^2 + \sigma_{yy}{}^2 + \sigma_{zz}{}^2 - 2v\left(\sigma_{xx}\sigma_{yy} + \sigma_{xx}\sigma_{zz} + \sigma_{yy}\sigma_{zz}\right) + 2(1+v)\left(\sigma_{xy}{}^2 + \sigma_{xz}{}^2 + \sigma_{yz}{}^2\right)\right]$$

Where

$$\sigma_{xx} = \lambda e + 2G\varepsilon_{xx} - c\Delta T \qquad \sigma_{yy} = \lambda e + 2G\varepsilon_{yy} - c\Delta T \quad \sigma_{zz} = \lambda e + 2G\varepsilon_{zz} - c\Delta T$$

$$\sigma_{xy} = 2G\varepsilon_{xy} \qquad \sigma_{xz} = 2G\varepsilon_{xz} \qquad \sigma_{yz} = 2G\varepsilon_{yz}$$

Where

$$c = (3\lambda + 2G)\alpha = \frac{E\alpha}{(1 + 2v)}$$

4.5 Hyperelastic material models

For isotropic hyperelastic materials, the strain-energy function, W can be defined in terms of strain invariants $I_i\,(i = 1,2,3\,)$ or principal stretches $\lambda_i\,(i = 1,2,3\,)$ i.e.

$$I_1 = \lambda^2{}_1 + \lambda^2{}_2 + \lambda^2{}_3$$

$$I_2 = \lambda^2{}_1\lambda^2{}_2 + \lambda^2{}_2\lambda^2{}_3 + \lambda^2{}_3\lambda^2{}_1$$

$$I_3 = \lambda^2{}_1\lambda^2{}_2\lambda^2{}_3$$

Where

$I_1\,, I_2\; and\; I_3$ are the three strain invariants

$\lambda_1\,, \lambda_2\;\; and\; \lambda_3$ are the principal stretches

The volume ratio is defined as

$$J = \lambda_1\,\lambda_2\,\lambda_3 \;\; = \frac{V}{V_0}$$

$$W = W(I_1\,, I_2\,, I_3\,) \text{ or } W = W(\lambda_1\,, \lambda_2\,, \lambda_3\,) \qquad (1)$$

Where

W- Strain energy potential or strain energy function

Because the material incompressibility, we split the deviatoric (subscript d or with ‘bar’) and the volumetric (subscript b) terms of the strain energy function. As a result, the volumetric terms is a function of volume ratio J only.

$$W = W_d(\bar{I}_1\,, \bar{I}_2\,) + W_b(\mathrm{J})$$

$$W = W_d(\bar{\lambda}_1\,, \bar{\lambda}_2\,, \bar{\lambda}_3\,) + W_b(\mathrm{J})$$

Where the deviatoric principal stretches and deviatoric invariants are defined as (for p =1, 2, 3)

$$\bar{\lambda}_\mathrm{p} = J^{-1/3}\lambda_\mathrm{p}$$

$$\bar{I}_{\mathrm{p}} = J^{-2/3} I_{\mathrm{p}}$$

Note that $I_3 = J^2$, so that I_3 is not in use in the definition of W.

If incompressibility is assumed (i.e. $I_3 = 1$), equation (1) then reduces to a function of two variables only i.e. I_1 and I_2 .

Polyurethane tested is treated as isotropic, incompressible material. These assumption are valid within experimental reason since the material anisotropy is 10% and the Poisson ratio, v is 0.475 +/- 0.025 (Kanyanta and Ivankovic, 2010).Therefore isotropic incompressible hyperelastic material model were used in the choice of representative material model for polyurethane, shore grade 65, 75 and 85.

Mooney-Rivlin 5 provides the best fit to the range of experimental data. However other material model can also be used to best fit the model like isotropy due to it easy of convergence.

The compressible form of Mooney-Rivlin material mode is (Rivlin and Saunders, 1951)

$$W = C_{10}(\bar{I}_1 - 3) + C_{01}(\bar{I}_2 - 3) + \frac{1}{2}K(J-1)$$

Where the third term is a compressible part, and J is the determinant of the deformation gradient (or volume ratio). For incompressible material J=1 for Mooney-Rivlin equation can be written as;

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3)$$

For uni-axial tension, the change in the strain energy can be expressed in form of:

$$dW = \left(\frac{\partial \mathrm{W}}{\partial \lambda_1}\right) d\lambda_1$$

Which leads to the following form of Mooney- Rivlin constitutive relation:

$$\sigma_0 = 2\left(\lambda^2 - \frac{1}{\lambda}\right)\left[C_{10} + \frac{C_{01}}{\lambda}\right]$$

Where σ_0 represents engineering stress. In this case the cross sectional area changes with deformation and can be expressed as (Dargazany et al., 2010);

$$A = \frac{A_0}{\lambda}$$

Cauchy true stresses obtained as:

$$\sigma = 2C_{10}\left(\lambda - \frac{1}{\lambda^2}\right) + 2C_{01}\left(1 - \frac{1}{\lambda^2}\right)$$

5. Tensile test

5.1 Introduction

Tensile test in general for engineering materials are performed for several reasons. This is to ensure quality of material. Tensile test are measured during the development of new material and process, this is to ensure that different material and process can be compared (Brown, 1996). In addition, tensile test are used frequently to predict the behaviour of material under loading. The strength of material is the primary concern. The strength of material is measured in terms of either the stress necessary to cause breaking or tearing or the level of stress the material can withstand. In general the measure of strength are used with caution in engineering design with factor of safety (Davis, 2004). Another property of interest in material is its ductility, which is a function of how much the material can deform before it fracture. Although, not often ductility of material is incorporated directly in design. It is rather stated in the material specification to ensure quality and toughness. Material with low ductility in tensile test reveals low resistance to fracture under loading. Elastic property is another interesting material property, but this property is better measure during tensile test with ultra-sonic techniques, since it is more accurate techniques.

5.2 Tensile Properties

The material of interest in this thesis is polyurethane, to be specific, shore grade 65, 75 and 85. One of the properties of polyurethane is the ability to stretch and recover like most other engineering material. This property is achieved by the material property and aided by type of constituents used during the formulation process.

The tensile test of polyurethane can yield several different property of the material. Sometimes, the properties derived are totally independent of each other. And also the properties are related. At times, some of these properties are of more interest than the others, it dependence on what is been examine in the material. And also the parameters that are controlled. The general properties of polyurethane are listed below.

5.2.1 Tensile Stress

It is also called tensile modulus, it is defined as the force per unit of original cross sectional area of the polyurethane required to stretch the specimen to a stated elongation (Prisacariu and Scortanu, 2006). In polyurethane, the stress is not linear with strain.

Mathematically, the tensile stress can be calculated by the formula;

$$\sigma = \frac{F}{A_o}$$

Where

σ -Tensile Stress

F- Tensile force

A_o-Initial cross section.

5.2.2 Tensile Strength

The tensile strength is the first property of interest, it is the maximum tensile stress which the polyurethane is capable of developing. It is the force per unit of the original cross-section area which is applied at the time of rupture of the specimen. It also known as breaking load, breaking stress, and ultimate tensile strength. In general for elastomer, for a class of material that contain a lot of different polymers, the tensile strength can range from as low as 3.5 MPa (500 psi) to as high as 55.2 MPa (8.0 ksi); however, the great majority of common elastomers tend to fall in the range from 6.9 to 20.7 MPa (1.0 to3.0 ksi) (Davis, 2004). The tensile strength is read as the maximum stress attained in the engineering stress-strain diagram. In the calculation of the tensile strength the unstressed cross sectional area of the polyurethane is used. Using the cross sectional area at fracture will result to higher order magnitude obtained.

Mathematically this can be calculated by the formula;

$$\sigma_u = \frac{F_u}{A_o}$$

Where

σ_u- Ultimate tensile strength

F_u- Tensile force at rapture

A_o- Initial cross sectional area

5.2.3 Ultimate Elongation

The ultimate elongation is another very important property of Polyurethane. It is the elongation at the point of sample breaks. This property defines the polyurethane property. This property is used to define broad class of material. ASTM defines that any material that can be reversibly elongated to twice its unstressed length falls into the class of elastomer. The upper end of the range for rubber compounds is about 800%, and although the lower end is supposed to be 100% (a 100% increase of the unstressed reference dimension), some special compounds that fall slightly below 100% elongation still are accepted as elastomers (Davis, 2004).

In the calculation of the elongation the unstressed cross sectional area of the polyurethane is used. Using the cross sectional area at fracture will result to higher order magnitude obtained.

Residual elongation in polyurethane or permanent set is determine as, the tensile force applied to break a benchmarked dumbbell specimen, a period of relation and follows after which the two parts are fitted together and the distance between the marks is re-measured. The difference between the new measurement and the original measurement are expressed as a percentage of the original distance (Harwood J. A. C et al., 1966).

5.2.4 Modulus.

Another very important property of polyurethane is its modulus. This is also referred to as elongation. Polyurethane and other elastomer refer to their modulus in description. The most specific designation are such as 100% modulus, 200% modulus, 300% modulus and 400% modulus, other modulus are used but in rare occasion. It is important to know that the numbers generated by this modulus are not an engineering modulus in the normal sense of the term, they are stresses required to obtain given strains. The '100% modulus' is also refereed as M-100, is simply the stress required to elongate the rubber to twice its original length (Davis, 2004).

In addition, another interesting term of shore grade it the E-modulus. This term assist in converting the hardness of shore grade (Shore A, 20-80 or shore D, 30 to 85) into young modulus. For a durometer, reading in shore A, it is multiply by 0.0235. Then subtract 0.6403 form the result. Then find the inverse base – e logarithm of the result. The result is in megapascals for young modulus. Convert this result to pounds per square inch by multiply the result by 145.0377.

Mathematically the modulus can be calculated by the formula;

$$e = \frac{\Delta L}{L_o}$$

Where

e - Elongation
ΔL- Change in gauge length
L_o- Original gauge length

5.2.5 Tension set

The tension set of polyurethane is the less often used property than the others stated above. Often when elastomeric materials are stretched to the final rupture, the recovery in length of the two sections resulting from the break is less than complete. It is possible to measure the total length of the original reference dimension and calculate how much longer the total length of the two separate section is. This is usually express as a percentage. Some classes of elastomer will experience almost total recovery, while others will display tension set as high as 10% or greater. Tension set are also measured for specimen stretched to less than breaking elongation

5.3 Factors influencing Polyurethane properties.

Polyurethane are in the class of elastomer, which also in the class of rubber. Their molecular structure are enormously different from other material such as steel. Their complexity is a function of the numerous organic ingredient. That is why they tends to exhibit a wide range of characteristic. Here are some of the important factors that influence the polyurethane properties (Davis, 2004);

- Structuring of the molecular matrix
- Compounding
- Specimen preparation
- Specimen type
- Vulcanization parameters
- Temperature

5.4 Tensile test and conditioning equipment

Tensile test requires material and conditioning equipment for the testing specimen and also the environment where the test is carried out is also important. The polyurethane properties for testing to a large extent depends on the history before the test and the atmospheric condition under which the test is carried out. Conditions such as temperature and humidity under which the test sample was stored affects its properties of the test result. Also mechanical deformation before test and temperature and humidity at testing affect the PU properties. The above mentioned factors have to be controlled for reproduction and consistency of result (Brown, 1996).Conditioning refers specifically to the process of bringing the test pieces to the required conditions of temperature and perhaps humidity immediately before test, and storage refers to the period before and after the testing specimen is prepared (Brown, 1996). Here are the common equipment used for tensile test of shore grade 65, 75 and 85.

5.4.1 Tensile specimen

The typical specimen for tensile test is a dumbbell, as shown below in Figure 5.1: Dumbbell (Tensile test specimen) . It consists of enlarged ends or what is called shoulder for the gripping the specimen during the tensile test. The gauge section is the most important part of the specimen. The gauge section is reduced in area compare to the shoulder. This is done, so that deformation and failure will be localized in this area.

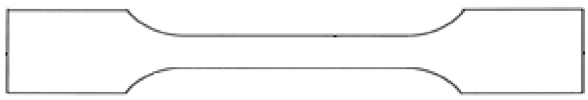


Figure 5.1: Dumbbell (Tensile test specimen)

The distances between the ends of the gauge section and the shoulders should be great enough so that the larger ends do not constrain deformation within the gauge section, and the gauge length should be great relative to its diameter. Otherwise, the stress state will be more complex than simple tension.

The standard (ASTMD412, 2013c) specifies three types of specimen for testing; the dumbbell-type cut from a standard test slab of die C with dimension 150 by 150 by 20m, the molded rings type and the straight specimen. Appendix 2 shows the detailed dimension of die C.

The molded ring type is standardized for the O-ring industry. For the dumbbell-type specimen, there are varieties of sizes that are permitted. Also, straight specimen is another type of specimen used in tensile test. It is not encouraging in the used of this specimen because of its tendency to break at the grip points. This usually result to unreliable result. The standard temperature for testing elastomer is 23 ± 2 °C (73.4 ± 3.6 °F). When testing is required for other temperatures, the standard condition for testing were referred to (ASTMD1349, 2014).

5.4.2 Tensile Test machine

The testing machine used for the tensile test is a universal tester, which test material in tension, compression, or bending. The primary function of this machine is to create the stress-strain curve, which is derived from the uni-axial tension on the shore grades.

In principle, there are two types of machines used in the tensile test of the specimen; electro-mechanical or hydraulic. The principal difference is the method by which the load is applied.

Electromechanical machines are based on variable speed electric motor; a gear reduction system; and one, two, or four screws that move the crosshead up or down. It is this motion that loads the specimen in tension or compression. The speed of the motor changes the crosshead speed. A microprocessor-based closed-loop servo system can be implemented to accurately control the speed of the crosshead. The Instron machine was used in the tensile test of the shore grades, it is an electro-mechanical type.

In general, electromechanical machines are capable of a wider range of test speeds and longer crosshead displacements, whereas hydraulic machines are more cost-effective for generating higher forces.

The other type of testing machine which was not used, the hydraulic testing machines are based on either a single or dual-acting piston that moves the crosshead up or down. However, most static hydraulic testing machines have a single acting piston or ram. In a manually operated machine, the operator adjusts the orifice of a pressure-compensated needle valve to control the rate of loading. In a closed-loop hydraulic servo system, the needle valve is replaced by an electrically operated servo valve for precise control.

The major parts of the equipment that are involved in the tensile test are the jaws used to grip the specimen, the temperature controlled chamber when temperature control is needed, and the cross head speed of 500 mm/min (ASTMD412, 2013c).

There are different method to determine the elongation of shore grade, visual, mechanical or optical. The degree of precision of these elongation measurement is not as precise as that of the used of extensometers.

The tensile test standard stated that three specimens are to be tested from each shore grade or elastomer group. Allowing for the median of the shore grade test being reported (ASTMD412, 2013c). Also there are provision for the use of five specimens on some occasions, with the median also being used, this occur when there is failure for the batch of the shore grade.

5.4.3 Air Conditioned Rooms

Polyurethane tensile testing is sensitive to the environmental condition where the experiment is conducted. The testing temperature and the room where the test is conducted is clearly stated in (ASTMD1349, 2014). The most important is humidity. Although if the test is conducted in the closed chamber, less attention should be placed on the laboratory condition.

5.4.4 Oven or furnace

The specimens that require high temperature are conditioned in the oven to attain the required temperature as stated in (ASTMD412, 2013c).It is stated that the minimum conditioning period for polyurethane is 12 hours, this ensures even distribution of temperature (ASTMD1349, 2014). Fluctuating humidity alters result and prevent repeatability of result, when test is carried in another laboratory.

5.4.6 Thermometer

The thermometer is used to measure the degree of hotness or coldness. During the tensile test the thermometer used was resistance thermometer to confirm the temperature of the furnaces used in conditioning the shore grade samples as against the furnace temperature display screen.

5.4.7 Refrigerator

The refrigerator was used for polyurethane specimen that need to be condition below room temperature. These shore grade were conditioned for minimum of 12 hours as stated by the standard, (ASTMD 1349, 2014). The tensile test is carried out in an enclosure so that the temperature is maintain in the test.

5.5 Tensile test result

The tensile test of shore grade 65, 75, 85 were performed as stated in the standard for rubber testing (ASTMD412, 2013c). The standard temperature of testing was also observed as stated in the standard (ASTMD1349, 2014). Figure 5.2- Figure 5.7 below show the results of tensile test.

5.5.1 Tensile test result shore grade 65, 75 and 85 at 20 °C

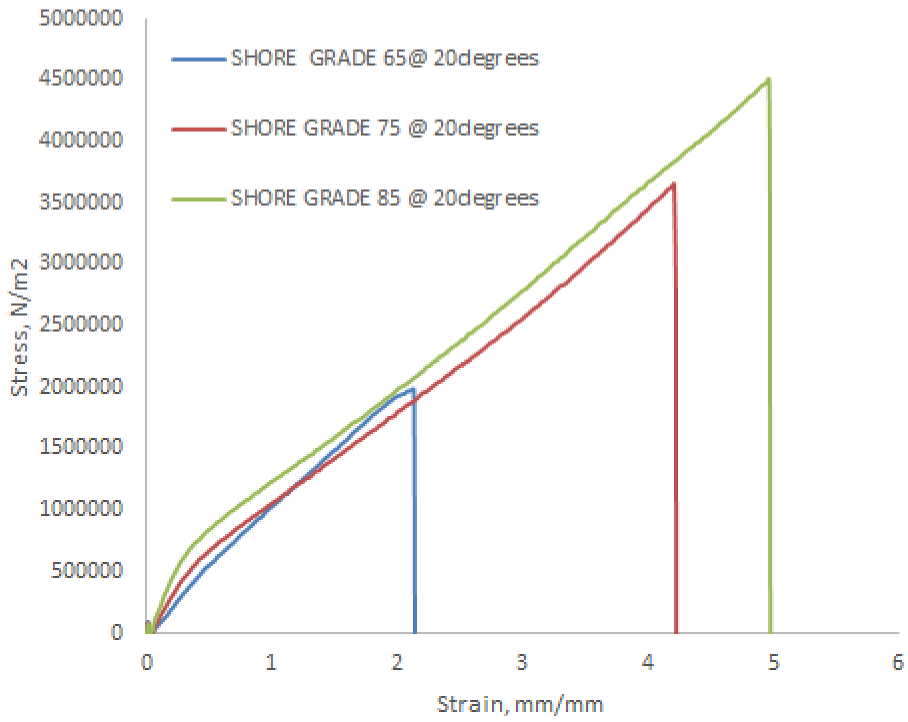


Figure 5.2: Tensile test result shore grade 65, 75 and 85 at 20 °C

Figure 5.2 shows the stress-strain graph of shore grade 65, 75 and 85 at 20°C. The shore grades show similar uni-axial stress-strain curves. There are significant difference in the ultimate stress and the ultimate elongation. Shore grade 85 has the highest ultimate stress and ultimate elongation. While shore grade 65 has the least ultimate stress and ultimate elongation. In addition, shore grade 85, has the highest young modulus (Patel et al., 2008), the young modulus of shore grade 65 and 75 are similar, but with that of shore grade 75 slightly higher. And since the young modulus is directly related to the stiffness, this implies that shore grade 65, 75 and 85 experience an increase in stiffness with shore grade 85 with the highest. Figure 5.2 further shows how the use of different ingredient in similar formula can result in some properties that are similar others vary substantially. It also shows that successive stress produces strain until rapture after which where the strain and stress goes to zero. See Appendix 3 for shore grade stress-strain data.

5.5.2 Tensile test result shore grade 65, 75 and 85 at 40 °C

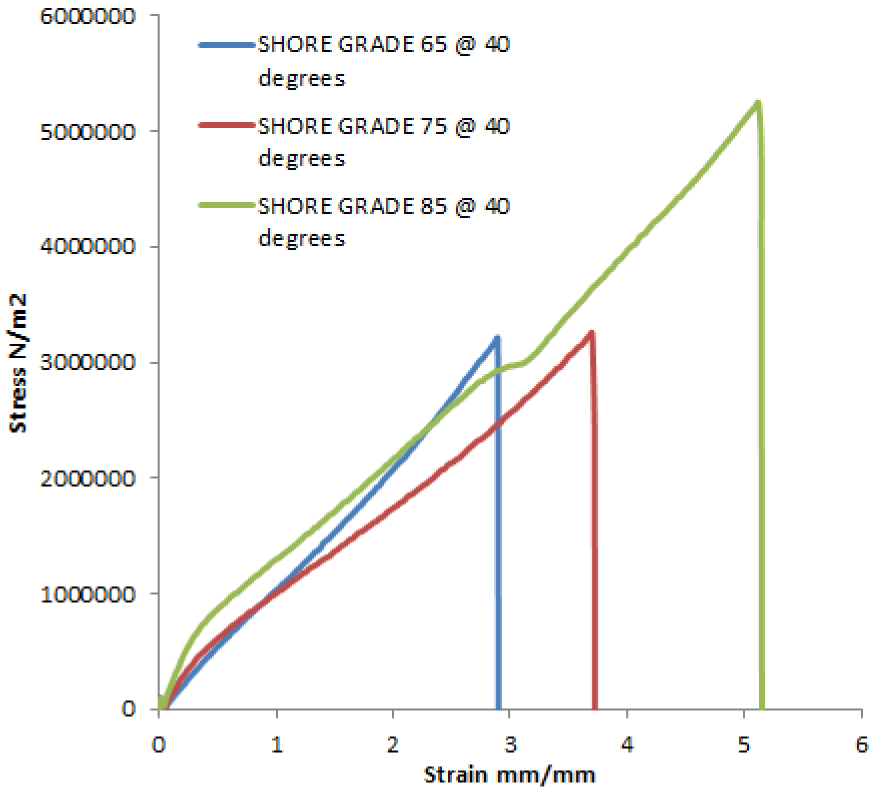


Figure 5.3 Tensile test result shore grade 65, 75 and 85 at 40 °C

Figure 5.3 shows the stress-strain graph of shore grade 65, 75 and 85 at 40°C. The shore grades show similar uni-axial stress-strain curves. There are significant difference in the ultimate stress and the ultimate elongation. Shore grade 85 has the highest ultimate stress and ultimate elongation. While shore grade 65 has the least ultimate elongation and not the least ultimate stress. The effect of temperature change is observed more in shore grade 65 and shore grade 75. In addition, the effect of temperature is visible with shore grade 85, it has slightly the highest young modulus (Patel et al., 2008), the young modulus of shore grade 65 and 75 are similar, but with that of shore grade 65 higher. And since the young modulus is directly related to the stiffness, this implies that shore grade 65, 75 and 85 experience an changes in stiffness as a result of temperature increase. Figure 5.3, further shows how the use of different ingredient in similar formula can result in some properties that are similar others vary substantially. It also shows that successive stress produces strain until rapture after which where the strain and stress goes to zero. See Appendix 3 for shore grade stress-strain data.

5.5.3 Tensile test result shore grade 65, 75 and 85 at 60 °C

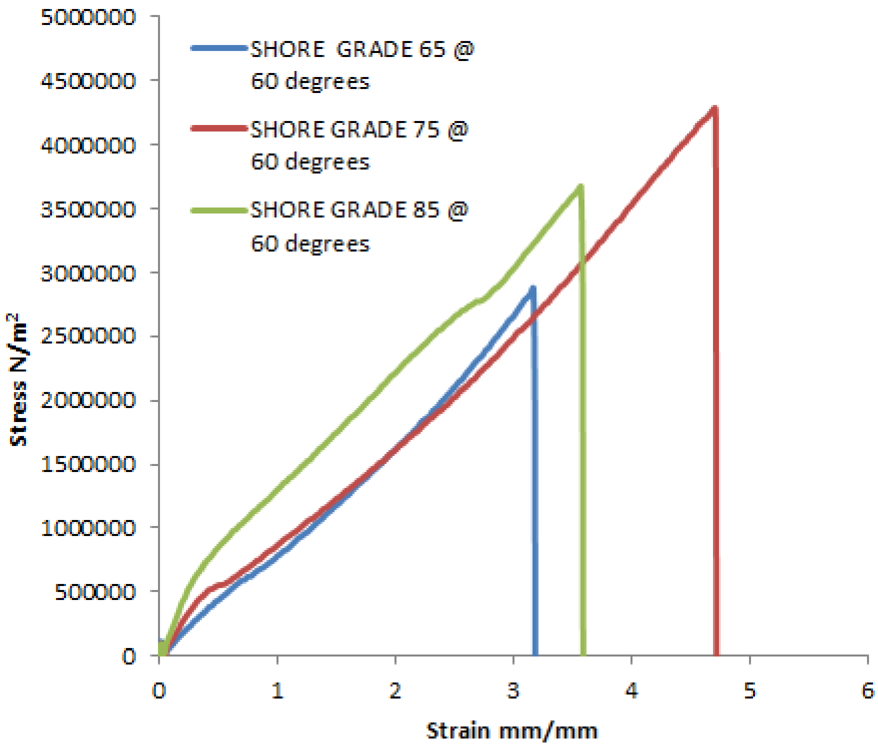


Figure 5.4: Tensile test result shore grade 65, 75 & 85 at 60 °C

Figure 5.4 shows the stress-strain graph of shore grade 65, 75 and 85 at 60°C. The shore grades show similar stress-strain curves. There are significant difference in the ultimate stress and the ultimate elongation. Shore grade 75 has the highest ultimate stress and ultimate elongation. While shore grade 65 has the least ultimate elongation and the least ultimate stress. The effect of temperature change is observed more in shore grade 85, which shows a reduction in the ultimate stress and elongation as compared to same shore grades at 20°C. In addition, the effect of temperature is visible with shore grade 85 with highest young modulus (Patel et al., 2008), the young modulus of shore grade 65 and 75 are similar and almost the same. And since the young modulus is directly related to the stiffness, this implies that shore grade 65, 75 and 85 experience changes in stiffness as a result of temperature increase. Figure 5.4, further shows how the use of different ingredient in similar formula can result in some properties that are similar others vary substantially. It also shows that successive stress produces strain until rapture after which where the strain and stress goes to zero. See Appendix 3 for shore grade stress-strain data.

5.5.4 Tensile test result shore grade 65, 75 and 85 at 70 °C

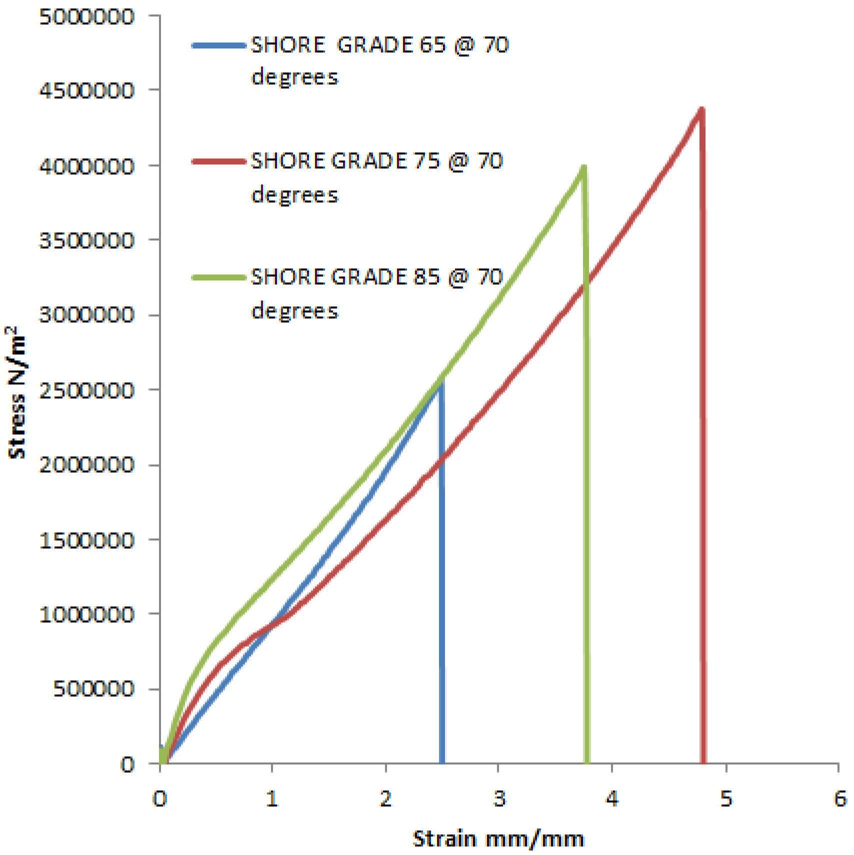


Figure 5.5: Tensile test result shore grade 65, 75 and 85 at 70 °C

Figure 5.5 shows the stress-strain graph of shore grade 65, 75 and 85 at 70^{o}C. The shore grades show similar stress-strain curves. There are significant difference in the ultimate stress and the ultimate elongation. Shore grade 75 has the highest ultimate stress and ultimate elongation. While shore grade 65 has the least ultimate elongation and the ultimate stress. The effect of temperature change is observed more in shore grade 85, which shows a reduction in the ultimate stress and elongation as compared to 20^{o}C. In addition, the effect of temperature is visible with shore grade 85, has the highest young modulus (Patel et al., 2008), the young modulus of shore grade 65 and 75 are similar, but with that of shore grade 65 higher. And since the young modulus is directly related to the stiffness, this implies that shore grade 65, 75 and 85 experience an changes in stiffness as a result of temperature increase. This graph shows how the use of different ingredient in similar formula can result in some properties that are similar others vary substantially. It also shows that successive stress produces strain until rapture after which where the strain and stress goes to zero. See Appendix 3 for shore grade stress-strain data.

5.5.5 Tensile test result shore grade 65, 75 and 85 at 80 °C

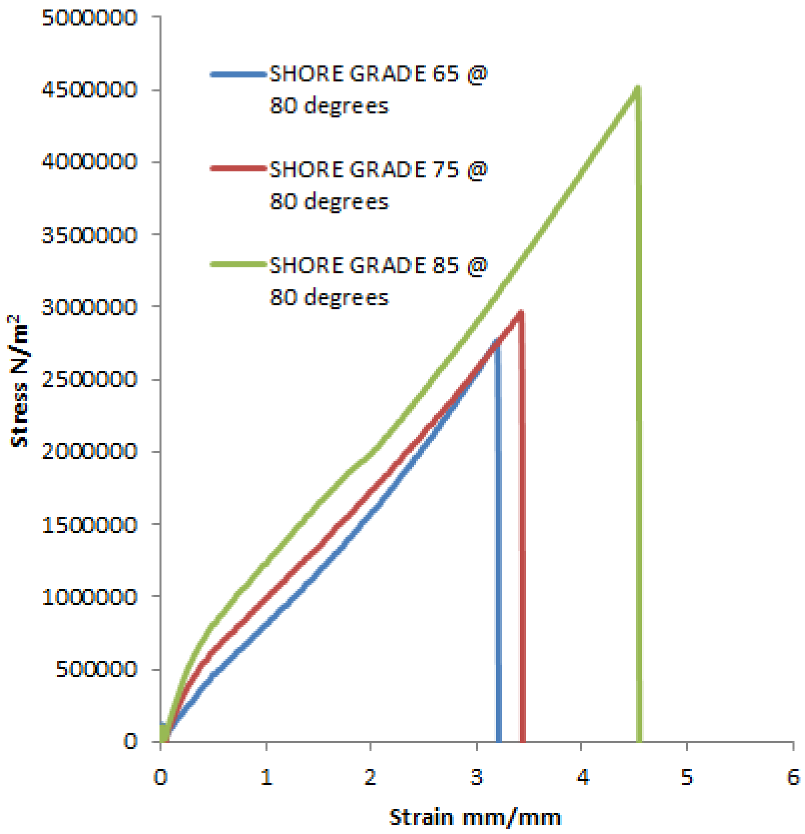


Figure 5.6: Tensile test result shore grade 65, 75 and 85 at 80 °C

Figure 5.6 shows the stress-strain graph of shore grade 65, 75 and 85 at 80°C. The shore grades show similar stress-strain curves. There are significant difference in the ultimate stress and the ultimate elongation. Shore grade 85 has the highest ultimate stress and ultimate elongation. While shore grade 65 has the least ultimate elongation and the least ultimate stress. The effect of temperature change is observed more in shore grade 75, which shows a reduction in the ultimate stress and elongation as compared to 20°C. In addition, the effect of temperature is visible with shore grade 85, has the highest young modulus (Patel et al., 2008), the young modulus of shore grade 65 and 75 are similar, but with that of shore grade 75 slightly higher. And since the young modulus is directly related to the stiffness, this implies that shore grade 65, 75 and 85 experience an changes in stiffness as a result of temperature increase. It further shows how the use of different ingredient in similar formula can result in some properties that are similar others vary substantially. It also shows that successive stress produces strain until rapture after which where the strain and stress goes to zero. See Appendix 3 for shore grade stress-strain data.

5.6 Typical failure mode of polyurethane during tensile test

From Figure 5.8: Shore grade 65, 75 and 85 failure mode, it is observed that failure of the polyurethane specimen during the tensile test, irrespective of the shore grades occur before the shoulder, curve area of the shore grade. This shows that the failure is not due to manufacture error, or stress concentration. For stress concentration the failure would have occurred in the curve (shoulder) area. The failure of the shore grade is as a result of strain concentration. Hence the failures occur before the shoulder and not in the shoulder region. Using the same tensile machine for steel, the failures occur at the length of the specimens and not close to the shoulder of specimens.

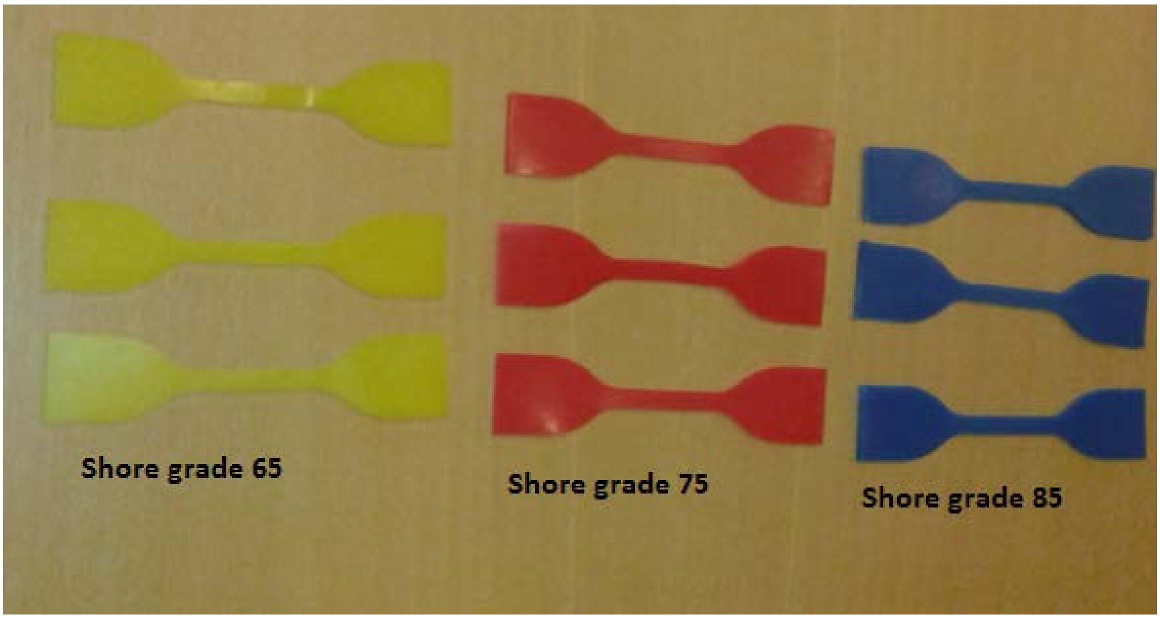


Figure 5.7: Shore grade 65, 75 and 85 before tensile test

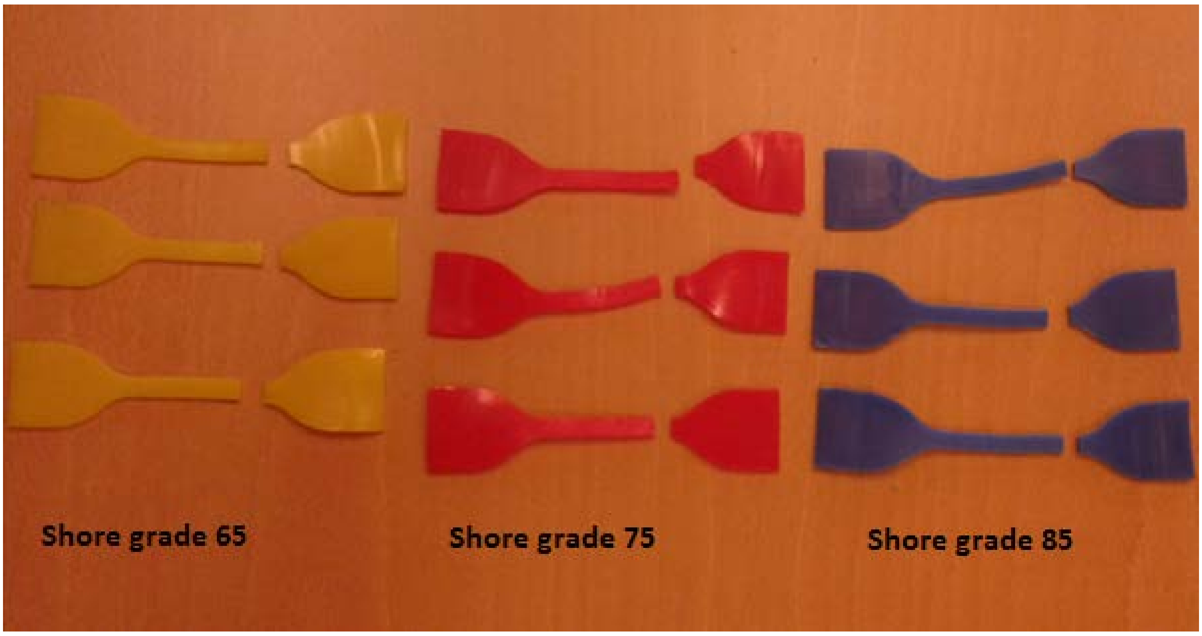


Figure 5.8: Shore grade 65, 75 and 85 failure mode

6. Design Methodology

6.1 Introduction

The design of bi-directional pig for pipeline cleaning was carried out according to IK AS design guideline for pig design (Appendix 4 for IK standard). While polyurethane tensile testing was carried in accordance to standard guidelines (ASTM D412, 2013).

According to IK AS design standard, the polyurethane diameter is greater than the internal diameter of the pipeline but not greater that the outer diameter. This will ensure good sealing of the internal pipe while cleaning of the pipeline is occurring simultaneously (Appendix 4 for IK standard for seal and pipeline size).

According to standard the surface of the polyurethane for tensile test should be free of surface roughness (ASTM D412, 2013). The first point of check is that the dies to be used should be sharp and free of nicks in order to prevent roughness of the edges of the polyurethanes which will cause the polyurethane tensile test to fail prematurely.

If the polyurethane is found to be with rough edges, it is abandon and should not be used for the tensile test of polyurethane. Also three samples of shore grades are tested for each temperature and the median test selected (ASTMD412, 2013a). The selected median test result was used as engineering material in static and transient dynamic analysis of shore grade.

6.1.1 Design objectives.

The primary objective of this thesis is to develop a deeper understanding of keeping pipeline as much as possible to the as-built condition. In another words, keeping maximum continuous flow as that of the design state, this tends to reduce cost and also increase the life span of the pipeline. This will be achieved by the understanding of the material (polyurethane) for sealing and cleaning the pipeline during pigging operation. The structure of this thesis is divided into three parts.

- The first stage involves the determination of the material properties of polyurethane for shore grade (65, 75 and 85) at different temperatures (20°C, 40°C, 60°C, 70°C and 80°C). The understanding of shore grade 65, 75 and 85 behaviour will be achieved from the stress-strain curve of the polyurethane at different temperature using the aid of tensile test machine. In other word, these shore grade will be subjected to axial tension test, from which the stress-strain data of these shore grade will be derived, this part had been covered in Chapter 5; Tensile test. The stress-strain data of every engineering material represents the material behavior, hence that of shore grades (65, 75 and 85). And also the temperature increase, reflect the different temperature the polyurethane is subjected to during cleaning operation. Tensile test of polyurethane at different temperature is to capture the material properties at different temperature.

- The second part of the thesis is using the stress -strain curves as an input to generate finite element model of the seal disc geometry to determine resulting deflection, static reacting forces on the wall and plot curves for shore grades (65, 75 and 85) and at temperatures (20°C, 40°C, 60°C, 70°C and 80°C). This will be achieved by step incremental displacement on the pig disc into the 8’’ pipeline for it to generate the static behavior of the pig.

- The third part of the thesis will involve the use of stress-strain data to perform transient dynamic analysis of a bi-directional pig (seal disc at both ends) flowing in water at 20°C and also to determine the time to travel through one end of a 12m test rig. Also the resulting deflection, “kinetic reacting forces on the wall” and “kinetic friction” are determined. Plot curves for different shore grades at temperature of 20°C.

The design processes followed in characterizing and understanding the dynamic behavior of polyurethane (shore grade 65, 75 and 85) are stated below;

a) Selection of material and tensile test

The primary material for the thesis is polyurethane, shore grade 65, 75 and 85. Dumbbell ‘Dice C’ were used to cut the shore grades. The edges of the shore grades were free from roughness (ASTM D412, 2014). The samples are subjected to uni-axial tension, using the tensile machine and the median of the three tests was used for further analysis. The shore grade were heat treated in an oven or refrigerator for a period of minimum of 12 hours to attain the testing temperature (ASTM D412, 2014). Tensile Test of shore grade 65, 75 and 85 at temperature of 20°C, 40°C, 60°C, 70°C and 80°C were carried out.

The other major material is an 8’’ (inches) pipe schedule 40. This represents the pipeline which the pig will be modelled to clean and also used for field testing in IK AS Forus.

b) Mechanical model for static analysis

Due to the intricacies in the pipeline and pig design, inventor model was used for the mechanical model of both. For the static model, one face of the bi-directional pig was model. This is due to the fact that the reaction force acting on the PU and the pipe is to be examined when the pig is displaced into the pipe.

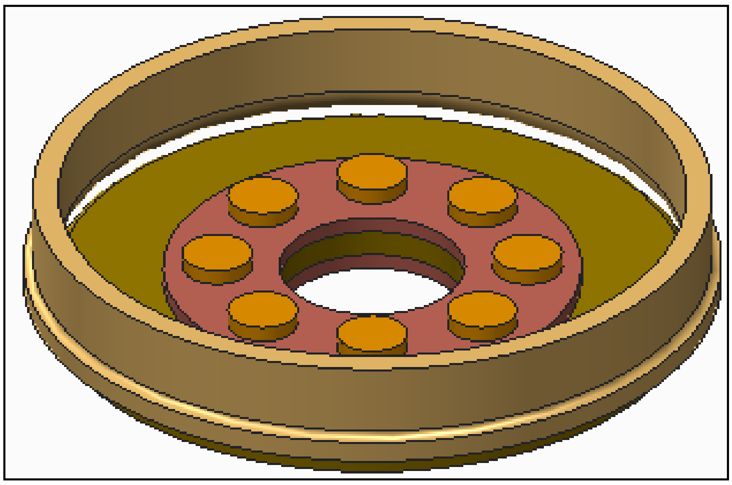


Figure 6.1: Pipe and one face of Polyurethane Pig for static analysis

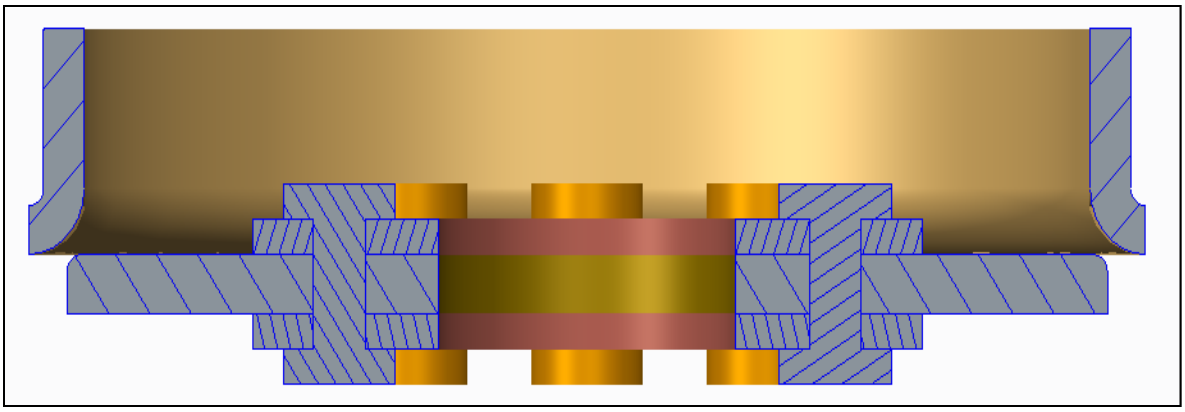


Figure 6.2: Section view of Pig and Pipe for static analysis

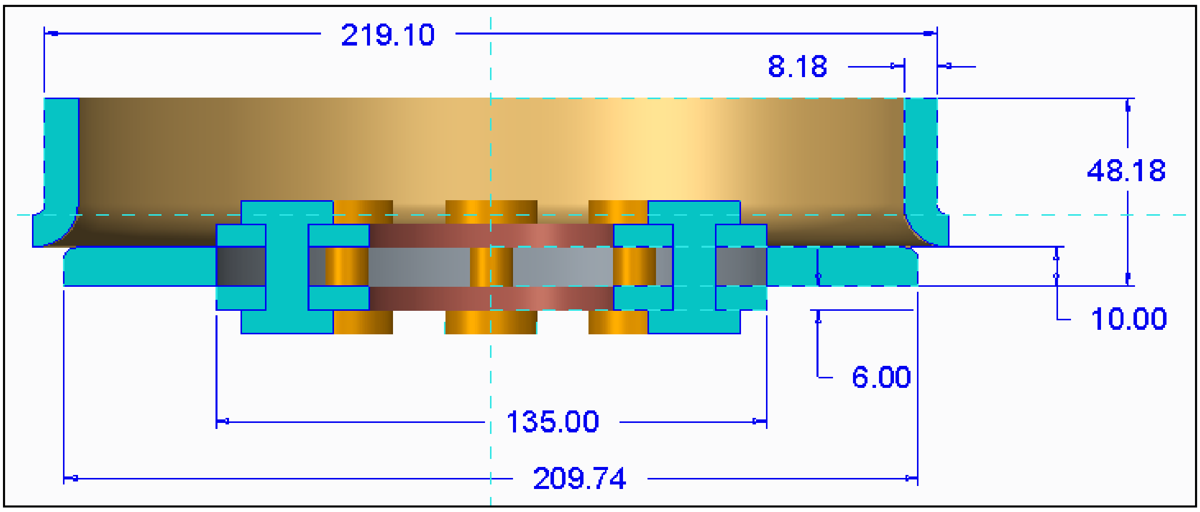


Figure 6.3: Pipe and PU with dimension

The static analysis is model with the knowledge that the flanges are steel and held tight to the PU by bolts, hence there will not be any potential deformation that can be observed. Further it is observed that the geometry is axis-symmetry and the highlighted cross section remain same across the revolution axis.

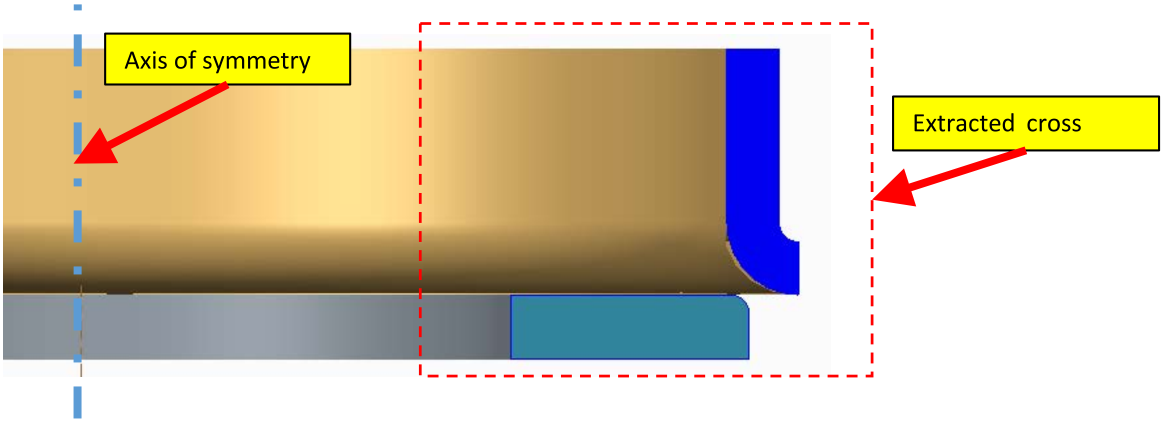


Figure 6.4: Axis-symmetry solution of static analysis

c) Finite element analysis for static analysis

In general the polyurethane is model to have initial 2mm contact with the pipeline of length 300mm. It was done so that ANSYS will recognize step displacement on the PU into the pipeline. Also the principle of plane stress and strain was applied in the model of the PU and pipe in the static analysis.

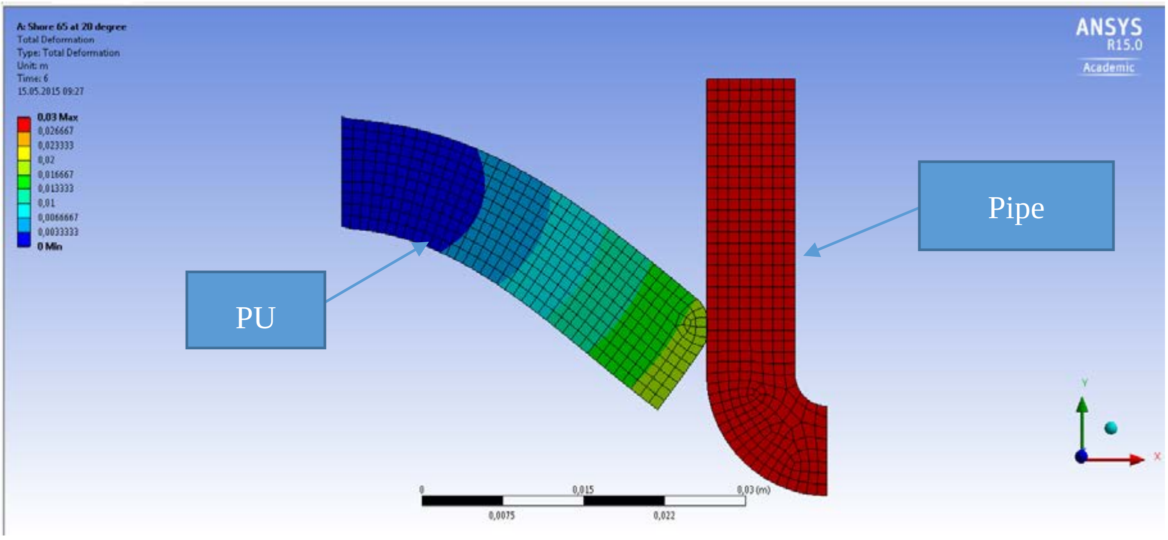


Figure 6.5 Pipe and PU showing plane stress principle

In this thesis, stress-strain data obtained from tensile test were used to determine the material parameter in hyperelastic model which in turn uses FEA software, ANSYS 15.0 to performed structural simulations on shore grade 65, 75 and 85 components.

Key assumptions related to the hyperelastic constitutive models in ANSYS, deformations are fully recoverable, thermal expansion is isotropic, material nearly or fully incompressible and the constitutive hyperelastic models are defined through a strain energy density function.

ANSYS has curve fitting tools to obtain material constant for hyperelastic models from the results obtained during the test. These result are fed into the ANSYS software in the form of text file for defined stress-strain data for uni-axial tension.

Immediately after the data were fed into ANSYS, the fitting process starts by choosing the Mooney-Rivlin strain energy function with two parameters. Based on the above procedure, ANSYS analyzes the data, and the material constants C_{10} and C_{01} become known. This material property data is either solved by using Moolen-Rivin 5, or isotropic material property. The later converges faster than the former.

d) Mechanical model for transient dynamic analysis

Due to the intricacies in the pipeline and pig design, inventor model was used for the mechanical model of both. For the static model, one face of the bi-directional pig was model. This is due to the fact that the reaction force acting on the PU and the pipe is to be examined when the pig is displaced into the pipe.

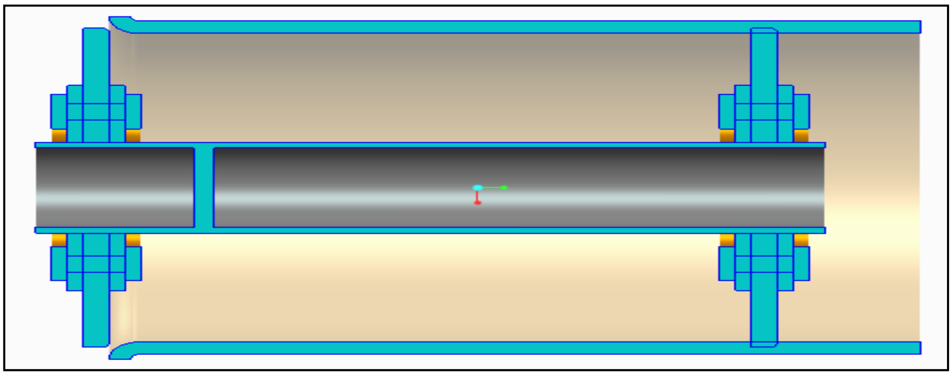


Figure 6.6: Section of pipe and entire pig for dynamic analysis

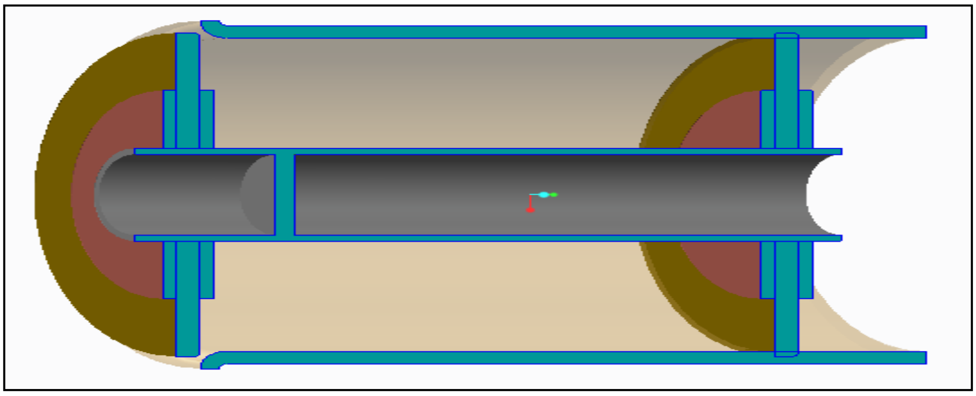


Figure 6.7: Section of pipe and entire Pig, showing PU for dynamic analysis

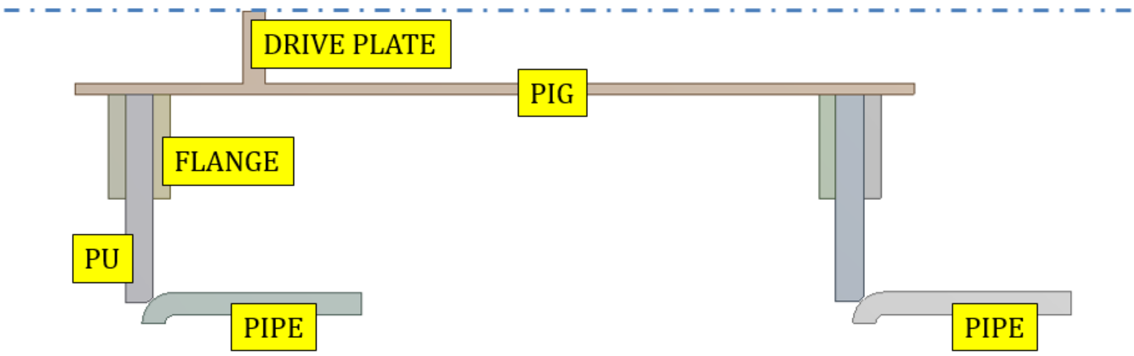


Figure 6.8: Axi-symmetry solution of dynamic analysis

e) Finite element analysis for transient dynamic analysis

The transient dynamic model was developed with explicit dynamic analysis. The model was developed with 2mm contact between the shore grade disc and the pipeline. This was done so that ANSYS will recognize the application of differential pressure on the PU into the pipeline. The principle of plane stress and strain was applied in the transient dynamic model.

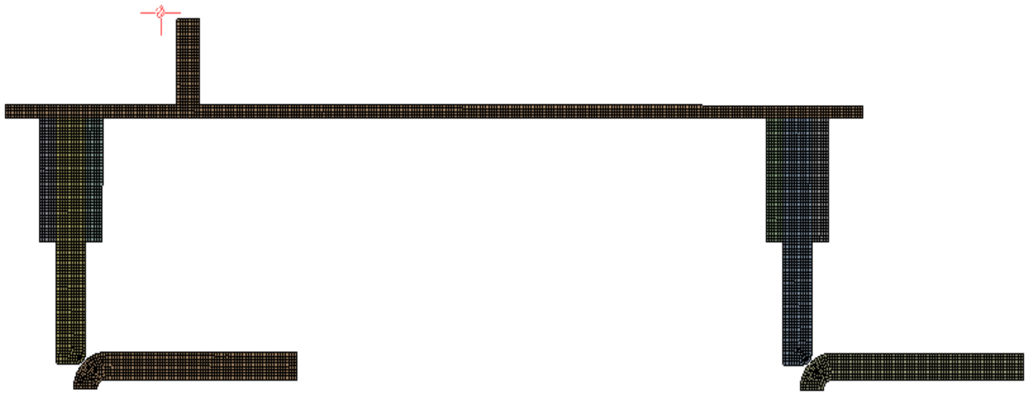


Figure 6.9: Explicit dynamic model showing contact and 1mm meshing

The stress-strain data obtained from tensile test were used to determine the material parameter in hyperelastic model which in turn uses FEA software, ANSYS 15.0 to performed structural simulations on shore grade 65, 75 and 85 components.

Key assumptions related to the hyperelastic constitutive models in ANSYS, deformations are fully recoverable, thermal expansion is isotropic, material nearly or fully incompressible and the constitutive hyperelastic models are defined through a strain energy density function.

ANSYS has curve fitting tools to obtain material constant for hyperelastic models from the results obtained during the test. These result are fed into the ANSYS software in the form of text file for defined stress-strain data for uni-axial tension.

Immediately after the data were fed into ANSYS, the fitting process starts by choosing the Mooney-Rivlin strain energy function with two parameters. Based on the above procedure, ANSYS analyzes the data, and the material constants C_{10} and C_{01} become known. This material property data is either solved by using Moolen-Rivin 5, or isotropic material property. The later converges faster than the former.

f) Analyzing finite element result

the finite element analysis was ran for shore grade 65, 75 and 85 with material property at temperature of 20°C, 40°C, 60°C, 70°C and 80°C.

For the static analysis, the deflection and the force at the wall of the pipeline were recorded and plotted.

For transient dynamic analysis, the time require for the pig to travel from one end to the other is recorded and also the kinetic reaction at the wall are recorded and plotted.

g) Analytical calculation.

This section detail the calculation of deflection, reaction forces and moment using the plate theory, and also using the material property of shore grade 65, 75 and 85.

7. Static Analysis Result of polyurethane

7.1 Introduction

One of the major objectives of this thesis work is to create models for shore 65, 75 and 85 with finite element analysis in order to determine the deflection and reaction forces experience by the polyurethane and the pipe wall during static condition. Plot of this reacting forces are shown with different temperature (20 °C, 40 °C, 60 °C, 70 °C, 80 °C).

ANSYS Workbench (finite element software) and inventor were used to model the pipe and the polyurethane (Shore grade 65, 75 and 85) and also run the analysis. The material property of shore grade 65, 75 and 85 at above temperature were got from the tensile test, the stress-strain property of the shore grade.

The static analysis was achieved by creating a 2mm contact between the pipeline of length 300mm and the shore grade polyurethane pig discs. And also a step-incremental displacement was imposed into the polyurethane pig discs assembly while keeping the pipeline fixed. Below are the result obtained in the static analysis.

7.1.1 Deflection

The deflection of shore grade 65, 75 and 85 is shown below. It is observed that the deflection is almost same for the step displacement and with temperature increase. Appendix 5 shows deflection of shore grade calculation results. This result is in-line with ANSYS result.

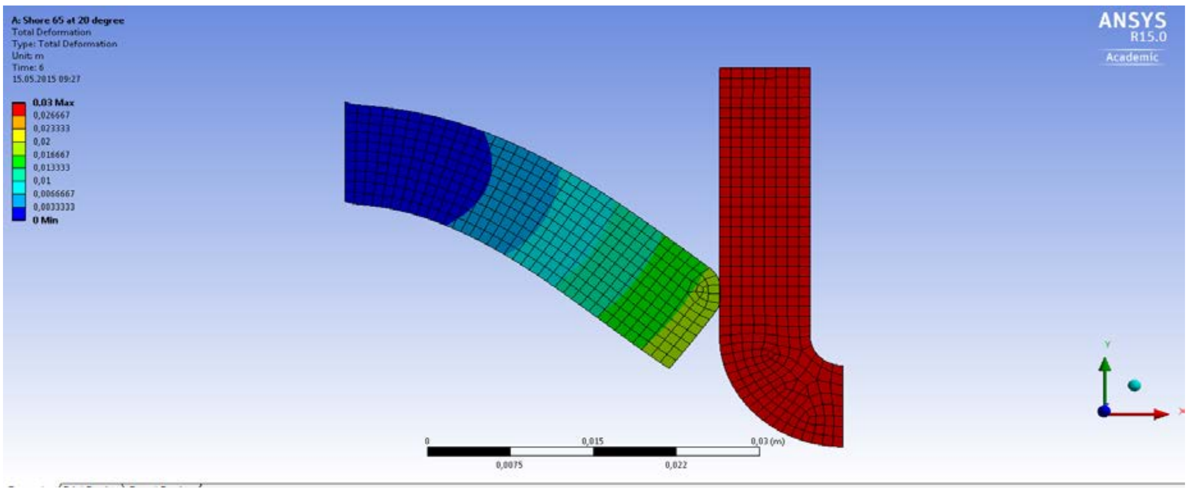


Figure 7.1: PU deflection

7.1.2 Reaction force at PU and pipewall

Figure 7.2 shows the contact between PU and pipe and also the axis of measurements (The point measurement of reaction force is the PU which has X and Y axis, also the pipe is another point of reaction force measurement with X and Y axis also). Figure 7.3 - Figure 7.17 show the result, reaction forces of static analysis of shore grade 65, 75 and 85 at temperature of 20 °C, 40 °C, 60 °C, 70 °C and 80 °C.

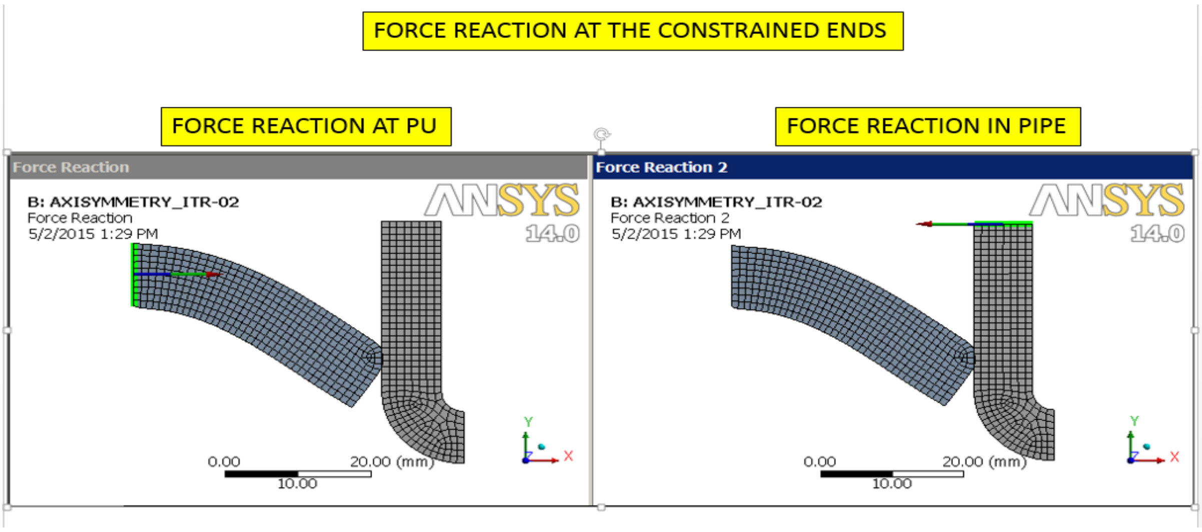


Figure 7.2: PU reaction force, constraints and applied axis

7.1.2.1 Shore grade 65 @ 20 °C reaction forces

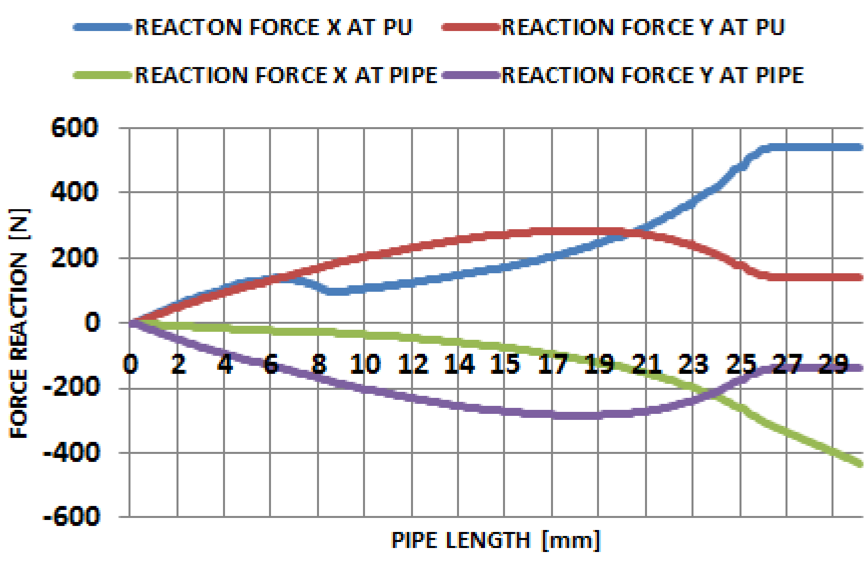


Figure 7.3: Reaction forces - shore grade 65 @ 20 °C

Figure 7.3 shows shore grade 65 at temperature of 20 °C. The reaction force at the PU is high when compare to that at the wall of the pipe since the pipe is rigid when compare to the flexible polyurethane material. The PU maximum reaction force at the X-axis is about 560N and that of the Y-axis is about 300N. While the maximum reaction forces on the pipe at the X-axis is about 420N and that of the Y-axis is about 300N. See Appendix 6 for the reaction data for shore grade 65 at 20 °C.

7.1.2.2 Shore grade 65 @ 40 °C reaction forces

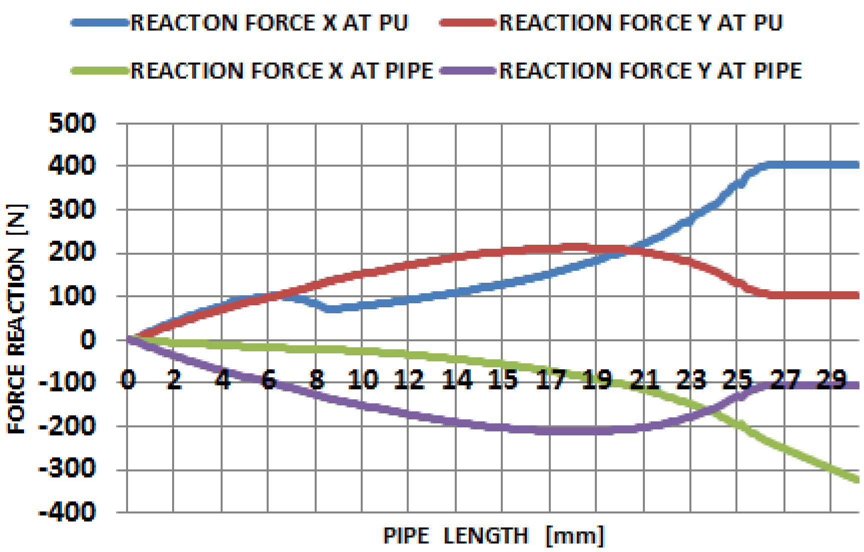


Figure 7.4: Reaction forces - shore grade 65 @ 40 °C

Figure 7.4 shows shore grade 65 at temperature of 40 °C. It is understood that as the temperature increases from 20 °C to 40 °C, the reaction forces will reduce as a result of strain, which is seen in the Figure 7.4 above. The reaction force at the PU is high when compare to that at the wall of the pipe since the pipe is rigid when compare to the flexible polyurethane material. The PU maximum reaction force at the X-axis is about 400N and that of the Y-axis is about 220N. While the maximum reaction forces on the pipe at the X-axis is about 320N and that of the Y-axis is about 220N. See Appendix 6 for the reaction data for shore grade 65 at 40 °C.

7.1.2.3 Shore grade 65 @ 60 °C reaction forces

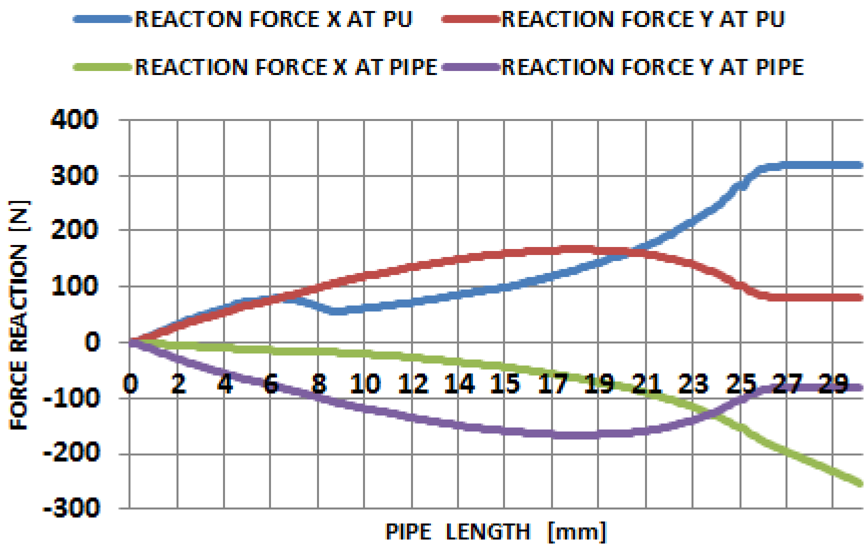


Figure 7.5: Reaction forces - shore grade 65 @ 60 °C

Figure 7.5 shows shore grade 65 at temperature of 60 °C. There is a reduction of reaction forces when compared to shore grade 65 at temperature of 20 °C, which is closer to room temperature, this is due to the fact that less force is required at the contact because of the increase in temperature of the PU due to strain. The reaction forces will reduce, which is seen in the Figure 7.5. The reaction force at the PU is high when compare to that at the wall of the pipe since the pipe is rigid when compare to the flexible polyurethane material. The PU maximum reaction force at the X-axis is about 400N and that of the Y-axis is about 220N. While the maximum reaction forces on the pipe at the X-axis is about 320N and that of the Y-axis is about 220N. See Appendix 6 for the reaction data for shore grade 65 at 60°C.

7.1.2.4 Shore grade 65 @ 70 °C reaction forces

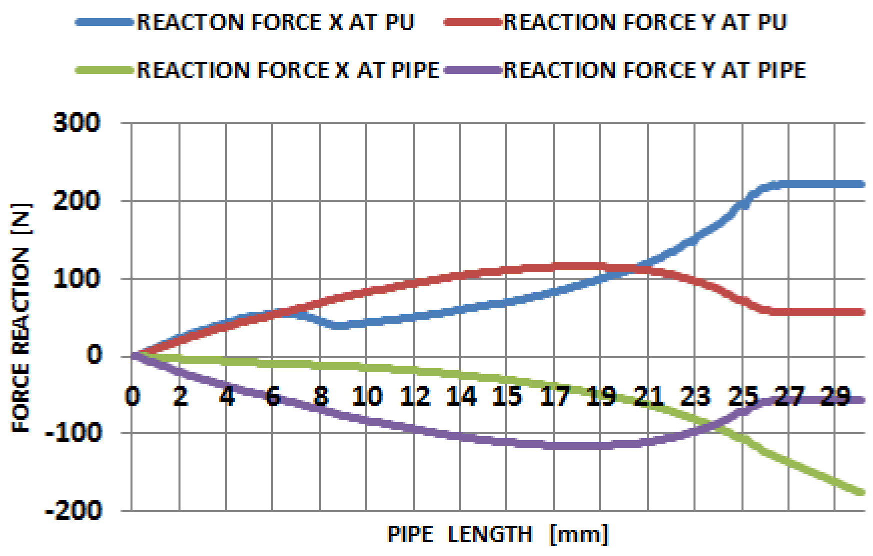


Figure 7.6: Reaction forces - shore grade 65 @ 70 °C

Figure 7.6 shows shore grade 65 at temperature of 70 °C. There is a reduction of reaction forces when compared shore grade 65 at temperature of 20 °C, which is closer to room temperature, this is due to the fact that less force is required at the contact because of the increase in temperature of the PU due to strain. The reaction forces will reduce, which is seen in the Figure 7.6. The reaction force at the PU is high when compare to that at the wall of the pipe since the pipe is rigid when compare to the flexible polyurethane material. The PU maximum reaction force at the X-axis is about 220N and that of the Y-axis is about 120N. While the maximum reaction forces on the pipe at the X-axis is about 180N and that of the Y-axis is about 120N. See Appendix 6 for the reaction data for shore grade 65 at 70 °C

7.1.2.5 Shore grade 65 @ 80 °C reaction forces

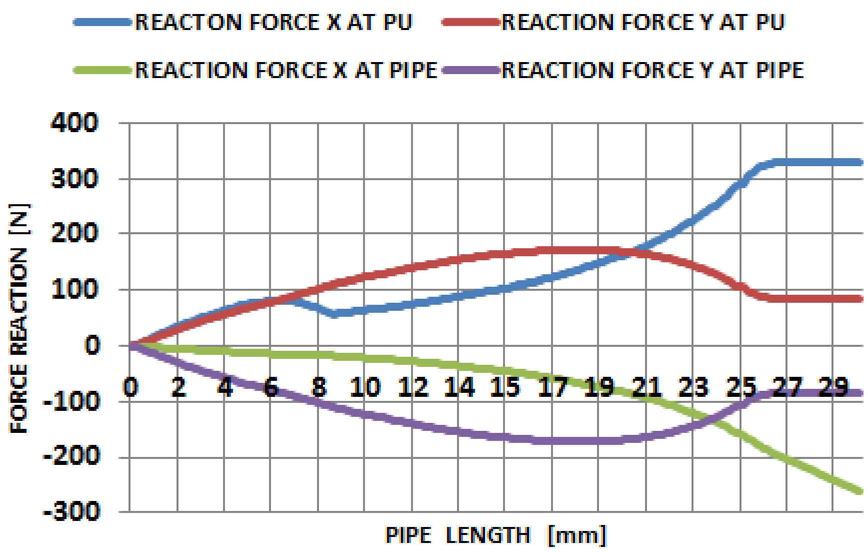


Figure 7.7: Reaction forces - shore grade 65 @ 80 °C

Figure 7.7 shows shore grade 65 at temperature of 80 °C. There is a reduction of reaction forces when compared to shore grade 65 at temperature of 20 °C, which is closer to room temperature, this is due to the fact that less force is required at the contact because of the increase in temperature of the PU due to strain on the material. The reaction forces will reduce, which is seen in the Figure 7.7 above. The reaction force at the PU is high when compare to that at the wall of the pipe since the pipe is rigid when compare to the flexible polyurethane material. The PU maximum reaction force at the X-axis is about 340N and that of the Y-axis is about 180N. While the maximum reaction forces on the pipe at the X-axis is about 260N and that of the Y-axis is about 180N. See Appendix 6 for the reaction data for shore grade 65 at 80 °C.

7.1.2.6 Shore grade 75 @ 20 °C reaction forces

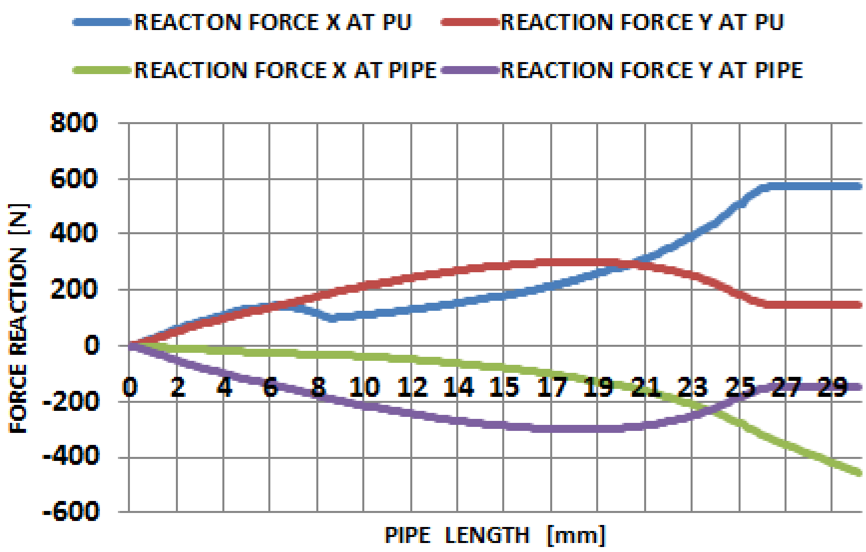


Figure 7.8: Reaction forces - shore grade 75 @ 20 °C

Figure 7.8 shows that higher reaction force at the PU and pipe wall, when shore grade75 is compared to that of 65 at 20 °C, this is due to the fact that shore grade 75 is stiffer than shore grade 65.

In the above diagram, The reaction force at the PU is high when compare to that at the wall of the pipe since the pipe is rigid when compare to the flexible polyurethane material. The PU maximum reaction force at the X-axis is about 590N and that of the Y-axis is about 320N. While the maximum reaction forces on the pipe at the X-axis is about 440N and that of the Y-axis is about 320N. See Appendix 6 for the reaction data for shore grade 75 at 20 °C.

7.1.2.7 Shore grade 75 @ 40 °C reaction forces

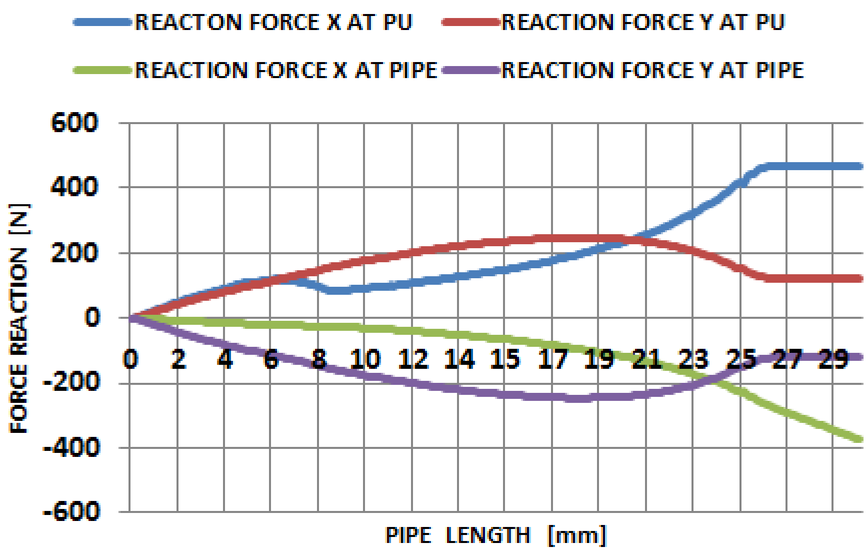


Figure 7.9: Reaction forces - shore grade 75 @ 40 °C

Figure 7.9 shows that higher reaction force at the PU and pipe wall, when shore grade 75 is compared to 65 at 40 °C, this is due to the fact that shore grade 75 is stiffer than shore grade 65. It is understood that as the temperature increases from 20 °C to 40 °C, the reaction forces will reduce due to strain, which is seen in the Figure 7.9 above. The reaction force at the PU is high when compare to that at the wall of the pipe since the pipe is rigid when compare to the flexible polyurethane material. The PU maximum reaction force at the X-axis is about 440N and that of the Y-axis is about 220N. While the maximum reaction forces on the pipe at the X-axis is about 380N and that of the Y-axis is about 220N. See Appendix 6 for the reaction data for shore grade 75 at 40 °C.

7.1.2.8 Shore grade 75 @ 60 °C reaction forces

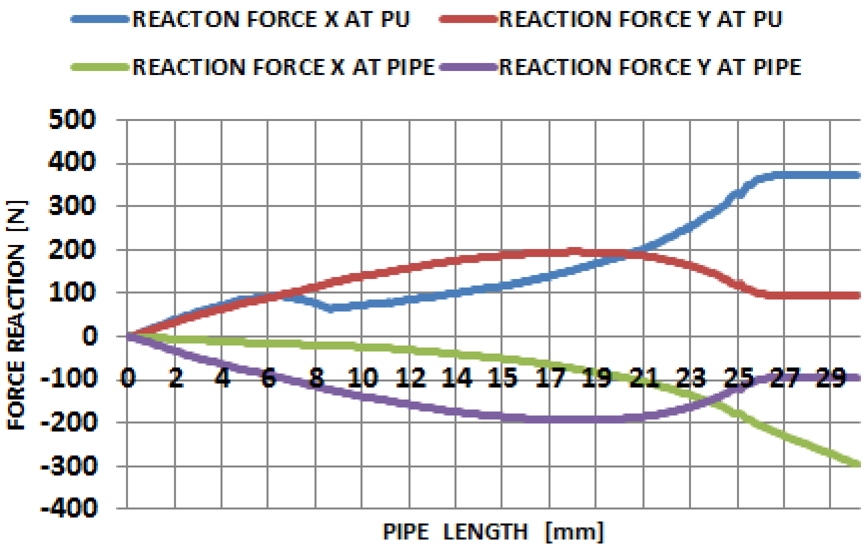


Figure 7.10: Reaction forces - shore grade 75@ 60 °C

Figure 7.10 shows that higher reaction force at the PU and pipe wall, when shore grade 75 is compared to 65 at 60 °C, this is due to the fact that shore grade 75 is stiffer than shore grade 65. Figure 7.10 shows shore grade 75 at temperature of 60 °C, it is understood that as the temperature increases from 20 °C to 60 °C, the reaction forces will reduce due to strain, which is seen in the Figure 7.10 above. The reaction force at the PU is high when compare to that at the wall of the pipe since the pipe is rigid when compare to the flexible polyurethane material. The PU maximum reaction force at the X-axis is about 380N and that of the Y-axis is about 200N. While the maximum reaction forces on the pipe at the X-axis is about 280N and that of the Y-axis is about 200N. See Appendix 6 for the reaction data for shore grade 75 at 60 °C.

7.1.2.9 Shore grade 75 @ 70 °C reaction forces

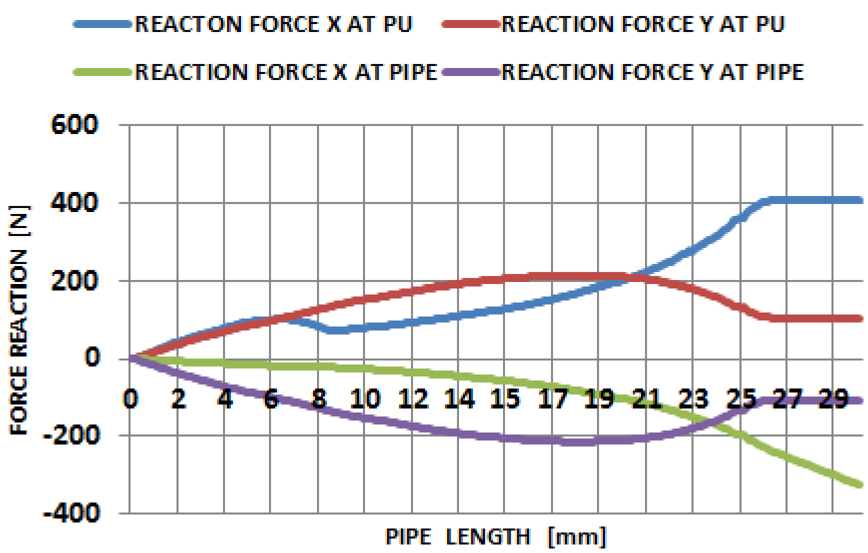


Figure 7.11: Reaction forces - shore grade 75@ 70 °C

Figure 7.11 shows that higher reaction force at the PU and pipe wall, when shore grade 75 is compared to 65 at 70 °C, this is due to the fact that shore grade 75 is stiffer than shore grade 65. Figure 7.11 shows shore grade 75 at temperature of 70 °C. It is understood that as the temperature increases from 20 °C to 70 °C, the reaction forces will reduce due to strain, which is seen in the Figure 7.11 above. The reaction force at the PU is high when compare to that at the wall of the pipe since the pipe is rigid when compare to the flexible polyurethane material. The PU maximum reaction force at the x-axis is about 400N and that of the Y-axis is about 200N. While the maximum reaction forces on the pipe at the x-axis is about 300N and that of the Y-axis is about 200N. See Appendix 6 for the reaction data for shore grade 75 at 70 °C

7.1.2.10 Shore grade 75 @ 80 °C reaction forces

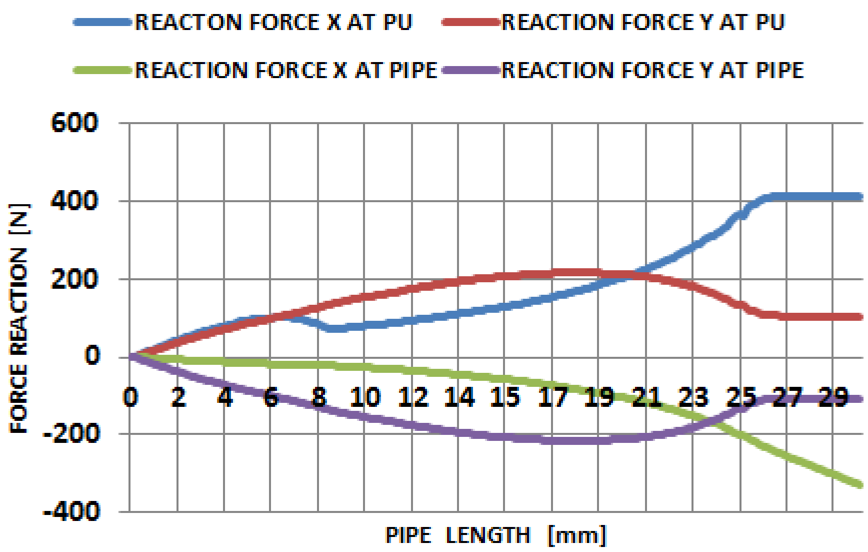


Figure 7.12: Reaction forces - shore grade 75 @ 80 °C

Figure 7.12 shows that higher reaction force at the PU and pipe wall, when shore grade 75 is compared to 65 at 80 °C, this is due to the fact that shore grade 75 is stiffer than shore grade 65. Figure 7.12 shows shore grade 75 at temperature of 80 °C, it is understood that as the temperature increases from 20 °C to 80 °C, the reaction forces will reduce due to strain, which is seen in Figure 7.12 above. The reaction force at the PU is higher when compare to that at the wall of the pipe since the pipe is rigid when compare to flexible polyurethane material. The PU maximum reaction force at the X-axis is about 400N and that of the Y-axis is about 200N. While the maximum reaction forces on the pipe at the X-axis is about 300N and that of the Y-axis is about 200N. See Appendix 6 for the reaction data for shore grade 75 @ 80 °C

7.1.2.11 Shore grade 85 @ 20 °C reaction forces

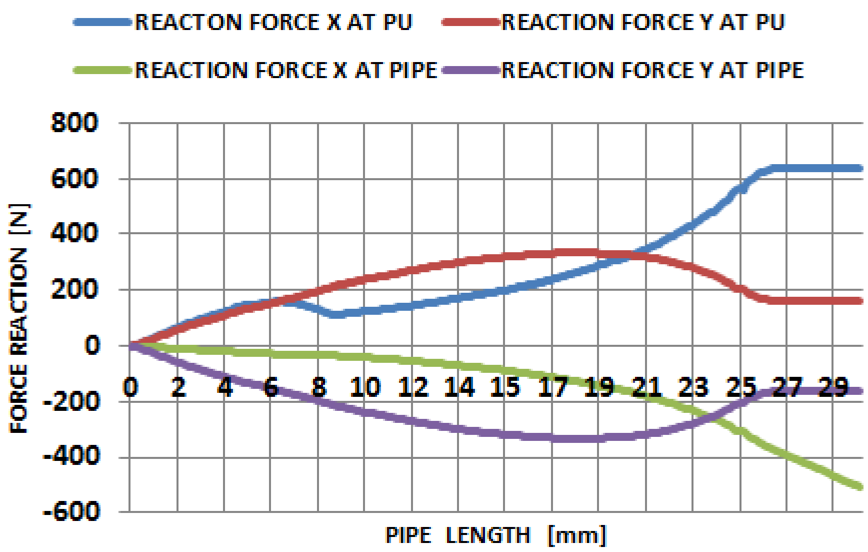


Figure 7.13: Reaction forces - shore grade 85@ 20 °C

Figure 7.13 shows that higher reaction force at the PU and pipe wall, when shore grade 85 is compared to that of 75 and 65 at 20 °C, this is due to the fact that shore grade 85 is stiffer than shore grade 75 and 65.

In the above Figure 7.13, The reaction force at the PU is high when compare to that at the wall of the pipe since the pipe is rigid when compare to the flexible polyurethane material. The PU maximum reaction force at the X-axis is about 640N and that of the Y-axis is about 360N. While the maximum reaction forces on the pipe at the X-axis is about 500N and that of the Y-axis is about 380N. See Appendix 6 for the reaction data for shore grade 85 at 20 °C

7.1.2.12 Shore grade 85 @ 40 °C reaction forces

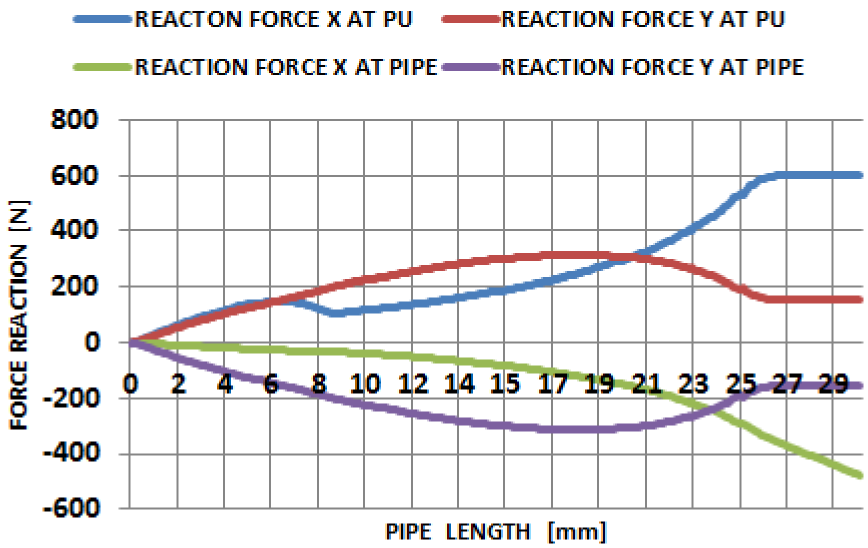


Figure 7.14: Reaction forces - shore grade 85@ 40 °C

Figure 7.14 shows that higher reaction force at the PU and pipe wall, when shore grade 85 is compared to 75 and 65 at 40 °C, this is due to the fact that shore grade 85 is stiffer than shore grade 75 and 65. Figure 7.14 shows shore grade 85 at temperature of 40 °C, it is understood that as the temperature increases from 20 °C to 40 °C, the reaction forces will reduce due to strain, which is seen in the Figure 7.14 above. The reaction force at the PU is high when compare to that at the wall of the pipe since the pipe is rigid when compare to the flexible polyurethane material. The PU maximum reaction force at the X-axis is about 600N and that of the Y-axis is about 300N. While the maximum reaction forces on the pipe at the X-axis is about 480N and that of the Y-axis is about 300N. See Appendix 6 for the reaction data for shore grade 85 at 40 °C.

7.1.2.13 Shore grade 85 @ 60 °C reaction forces

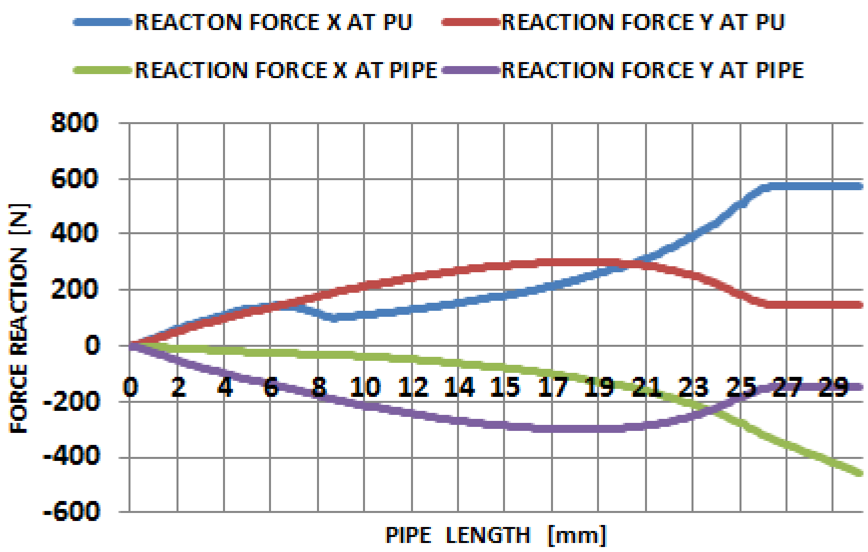


Figure 7.15: Reaction forces - shore grade 85@ 60 °C

Figure 7.15 shows that higher reaction force at the PU and pipe wall, when shore grade 85 is compared to 75 and 65 at 60 °C, this is due to the fact that shore grade 85 is stiffer than shore grade 75 and 65.

Figure 7.15 shows shore grade 85 at temperature of 60 °C. It is understood that as the temperature increases from 20 °C to 60 °C, the reaction forces will reduce, which is seen in the Figure 7.15 above. The reaction force at the PU is high when compare to that at the wall of the pipe since the pipe is rigid when compare to the flexible polyurethane material. The PU maximum reaction force at the X-axis is about 590N and that of the Y-axis is about 290N. While the maximum reaction forces on the pipe at the X-axis is about 440N and that of the Y-axis is about 290N. See Appendix 6 for the reaction data for shore grade 85 at 60 °C

7.1.2.14 Shore grade 85 @ 70 °C reaction forces

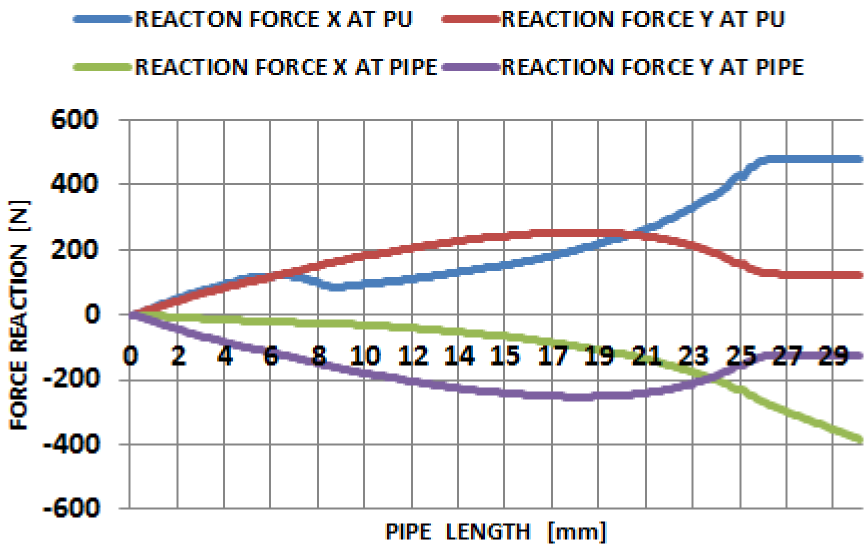


Figure 7.16: Reaction forces - shore grade 85@ 70 °C

Figure 7.16 shows that higher reaction force at the PU and pipe wall, when shore grade 75 is compared to 75 and 65 at 70 °C, this is due to the fact that shore grade 85 is stiffer than shore grade 75 and 65.

Figure 7.16 shows shore grade 85 at temperature of 70 °C. It is understood that as the temperature increases from 20 °C to 70 °C, the reaction forces will reduce due strain, which is seen in the Figure 7.16 above. The reaction force at the PU is high when compare to that at the wall of the pipe since the pipe is rigid when compare to the flexible polyurethane material. The PU maximum reaction force at the X-axis is about 480N and that of the Y-axis is about 280N. While the maximum reaction forces on the pipe at the X-axis is about 390N and that of the Y-axis is about 240N. See Appendix 6 for the reaction data for shore grade 85 at 70 °C

7.1.2.15 Shore grade 85 @ 80 °C reaction forces

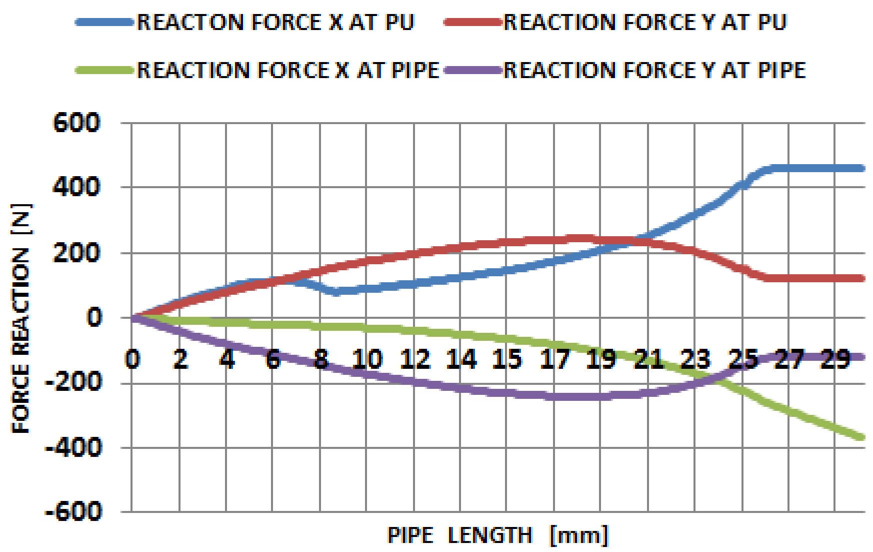


Figure 7.17: Reaction forces - shore grade 85@ 80 °C

Figure 7.17 shows that higher reaction force at the PU and pipe wall, when shore grade 85 is compared to 75 and 65 at 80 °C, this is due to the fact that shore grade 85 is stiffer than shore grade 75 and 65.

Figure 7.17 shows shore grade 85 at temperature of 80 °C. It is understood that as the temperature increases from 20 °C to 80 °C, the reaction forces will reduce due to strain, which is seen in the Figure 7.17 above. The reaction force at the PU is high when compare to that at the wall of the pipe since the pipe is rigid when compare to the flexible polyurethane material. The PU maximum reaction force at the X-axis is about 420N and that of the Y-axis is about 220N. While the maximum reaction forces on the pipe at the X-axis is about 380N and that of the Y-axis is about 220N. See Appendix 6 for the reaction data for shore grade 85 at 80 °C

7.2 PU reaction force with temperature changes.

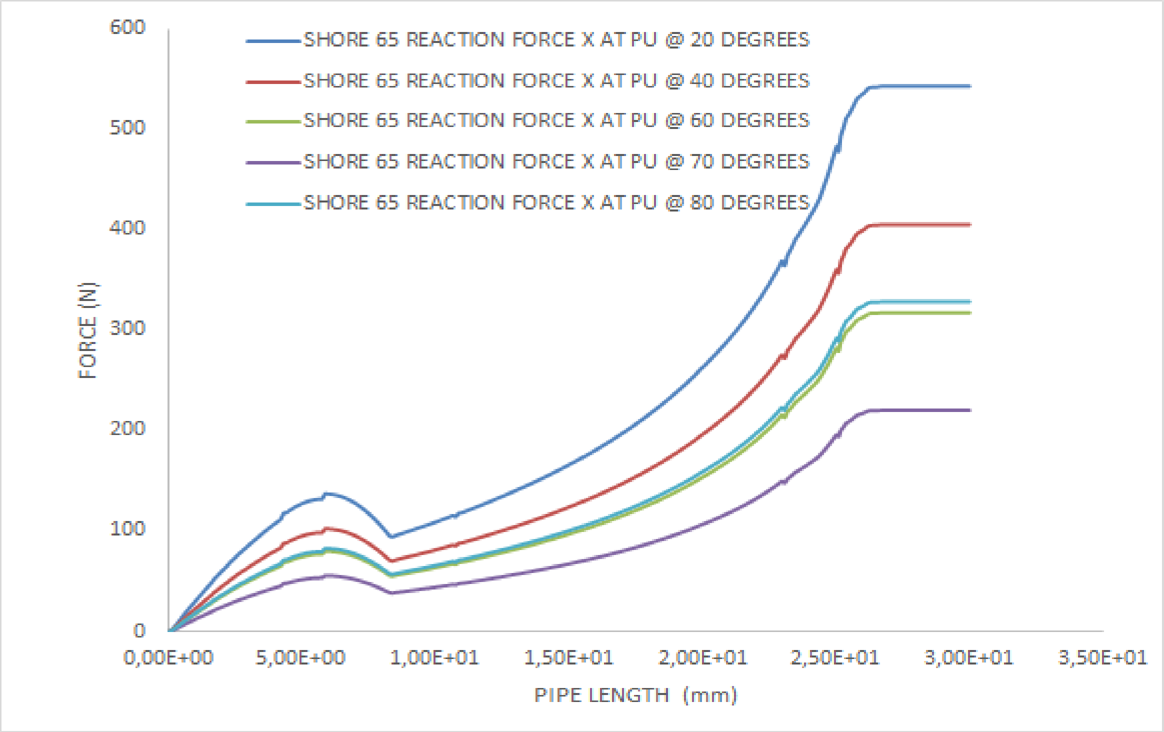


Figure 7.18: Shore grade 65 reaction force with temperature change

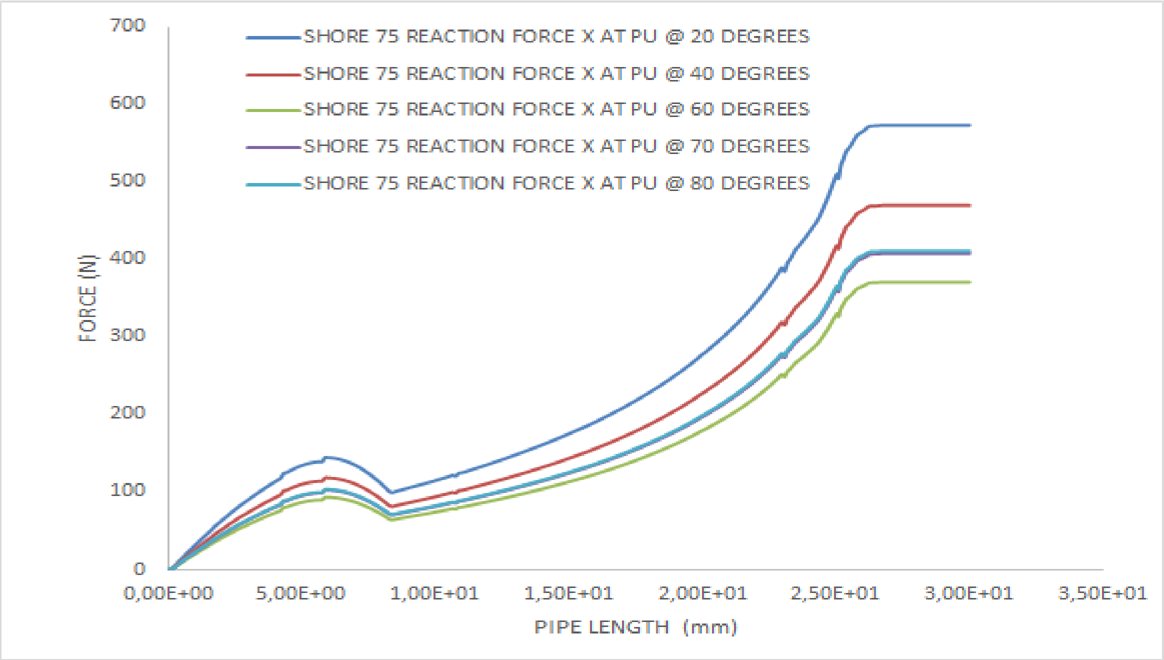


Figure 7.19: Shore grade 75 reaction force with temperature change

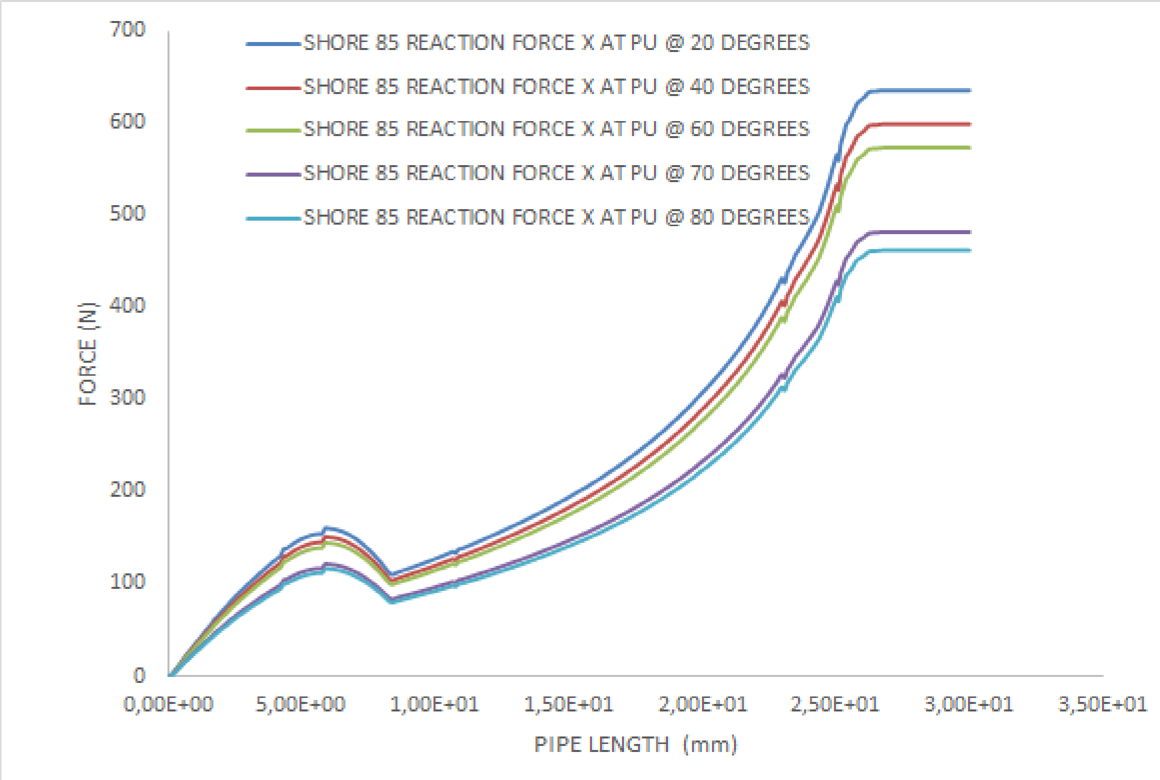


Figure 7.20: Shore grade 85 reaction force with temperature change

Figure 7.18-Figure 7.20 show the effect of temperatures changes on the reaction forces of shore grade 65, 75 and 85 on pipeline wall. It can be clearly observed with shore grade 85 that the increase in temperature result to lower reaction forces on the shore grade which is due to increase in strain experience by shore grade 85 as temperature increase. Similarly, shore grade 65 and 75 experience decrease in reaction forces on the pipeline wall due to temperature increase. In addition the reaction force on shore grade 85 is higher than shore 65, and 75 due to the higher stiffness of shore grade 85.

In addition, shore grade 65 at 70°C experiences the least force, this is due to fact that maximum strain occur at that temperature, that temperature (70°C) is suitable for pigging operation using shore grade 65 seal discs. While shore 75 is suitable for pigging operation at 60°C. In addition, shore 85 is suitable for pigging at 80°C also due to reduced reaction force between PU and pipewall as a result of maximum strain.

8. Transient dynamics result of polyurethane

8.1 Introduction

One of the major objectives of this thesis work is to generate model for shore 65, 75 and 85 with finite element analysis in order to determine the deflection, and reaction forces experience by the polyurethane and the pipe wall during transient dynamic condition. In addition, generation of plot of reacting forces at temperature 20°C.

Inventor was used to model the mechanical model of the pig and the pipeline because of the intricacies in the design of both. ANSYS Workbench, finite element software explicit dynamic was used to model the pipe and the polyurethane (Shore grade 65, 75 and 85) and also run the analysis in order to achieve the time of travel of the pig. The material property of shore grade 65, 75 and 85 at above temperature were got from the tensile test, the stress-strain property of the shore grade. In addition, static structural was used to model shore grade 65, 75 and 85 to determine the kinetic reaction forces.

The transient dynamic analysis was achieved by creating a 2mm contact between the pipe and the shore grade polyurethane. Differential pressures of 0.2 bar was imposed on the polyurethane assembly while keeping the pipeline fixed. The resulting deflection and reaction forces are shown below. 1 mm face meshing was used. Transient Material property is same as that used in the static analysis, this was derived from the stress-strain data during tensile tests.

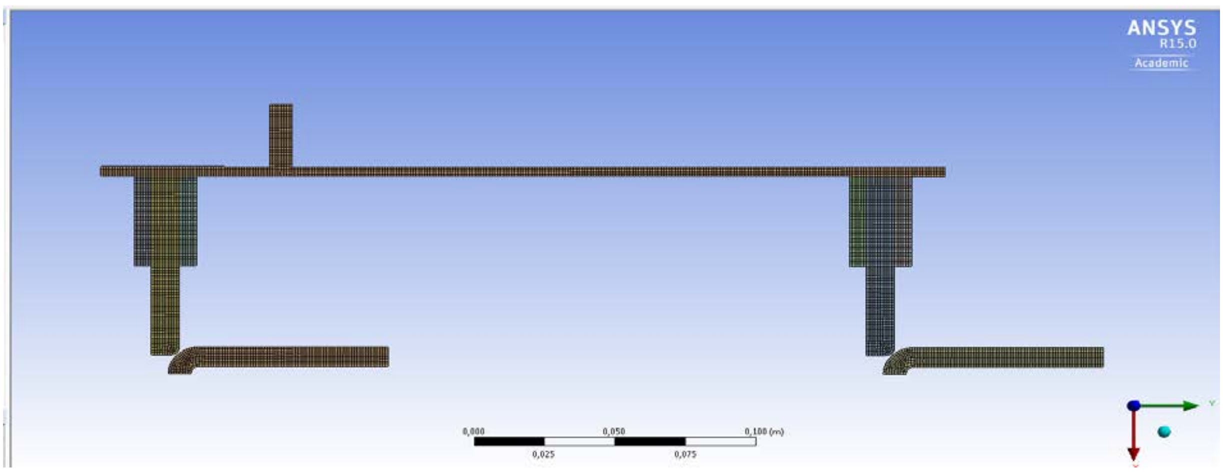


Figure 8.1: Transient dynamic model showing contact and mesh

8.2 Field Test

Field test was carried out in IK AS facility in Forus. The test involves testing shore grade 65, 75 and 85 pig in a 12m test rig. Details of test procedure can be found in Appendix 7, Test Procedure. In addition, Health and safety observed can be found in this document, 'Test Procedure'. The time required for shore grade 65, 75 and 85 pigs to travel from the pig launcher end to the receiver end was recorder. Easy view software was used for travel time measurement, records are shown in Appendix 8 Easy view record of pig travel time. Also, see Appendix 9 for detailed drawings of test rig and shore grade 65, 75 and 85 pig.

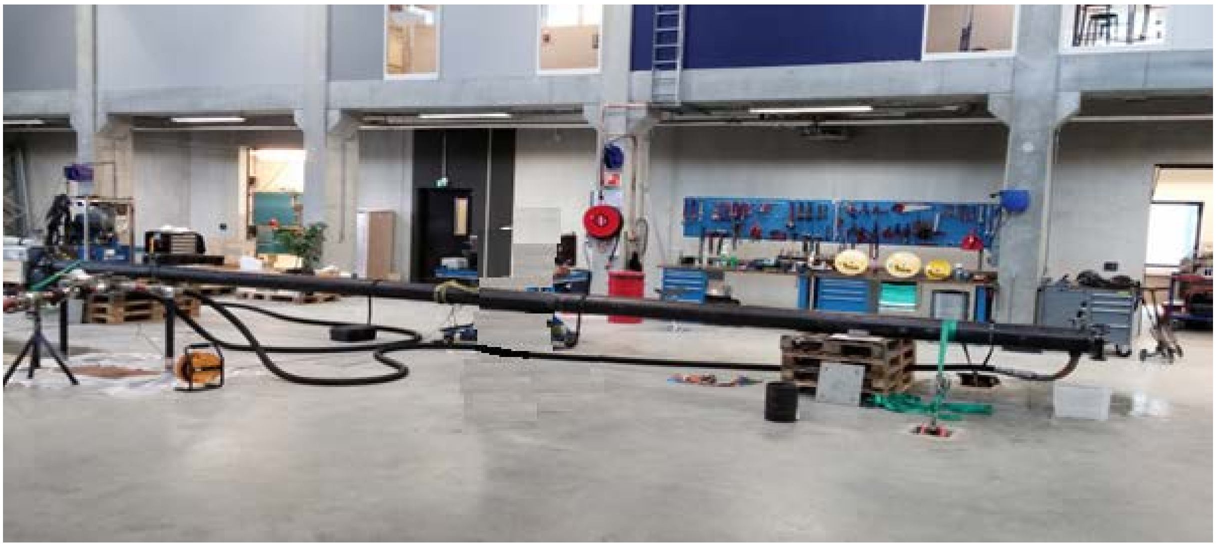


Figure 8.2: 12m Test rig

Figure 8.3: Shore grade 65 Pig

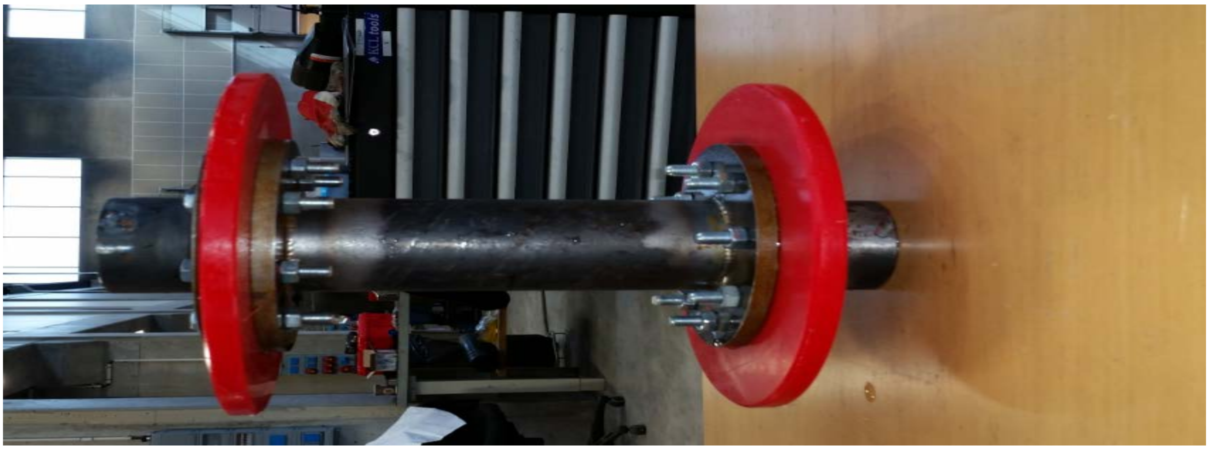


Figure 8.4: Shore grade 75 Pig

Figure 8.5: Shore grade 85 Pig

8.2.1 Transient dynamic analysis result- time of travel-ANSYS

Explicit dynamic was used to model the time travel for pig made of shore grade 65, 75 and 85 disc. A short section of the pipeline was model and the pig was ran in it. Table 8.1: Time of travel shore grade 65 - ANSYS result - Table 8.3: Time of travel shore grade 85 – ANSYS result show the ANSYS result.

a) Time of travel for shore grade 65 at 20 °C

Shore grade 65 at 20 °C	
Time (s)	Distance (m)
1,18E-38	0,0000000
3,50E-04	0,0000044
7,00E-04	0,0000153
1,05E-03	0,0000318
1,40E-03	0,0000539
1,75E-03	0,0000837
2,10E-03	0,0001200
2,45E-03	0,0001623
2,80E-03	0,0002112
3,15E-03	0,0002662
3,50E-03	0,0003272
3,85E-03	0,0003943
4,20E-03	0,0004675
4,55E-03	0,0005460
4,90E-03	0,0006302
5,25E-03	0,0007205
5,60E-03	0,0008170
5,95E-03	0,0009184
6,30E-03	0,0010254
6,65E-03	0,0011386
7,00E-03	0,0012578

Table 8.1: Time of travel shore grade 65 - ANSYS result

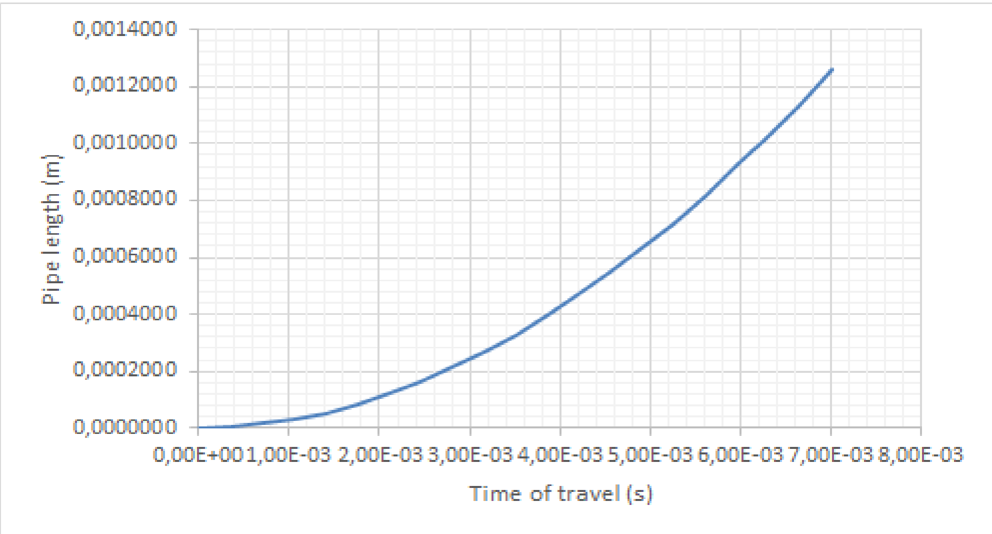


Figure 8.6: Time of travel shore grade 65 – ANSYS result

b) Time of travel for shore grade 75 at 20 °C

Shore grade 75 at 20 °C	
Time (s)	Distance (m)
1,18E-38	0,0000000
3,50E-04	0,0000044
7,00E-04	0,0000152
1,05E-03	0,0000318
1,40E-03	0,0000539
1,75E-03	0,0000835
2,10E-03	0,0001200
2,45E-03	0,0001622
2,80E-03	0,0002110
3,15E-03	0,0002660
3,50E-03	0,0003271
3,85E-03	0,0003936
4,20E-03	0,0004665
4,55E-03	0,0005452
4,90E-03	0,0006294
5,25E-03	0,0007192
5,60E-03	0,0008152
5,95E-03	0,0009169
6,30E-03	0,0010237
6,65E-03	0,0011364
7,00E-03	0,0012554

Table 8.2: Time of travel shore grade 75 - ANSYS result

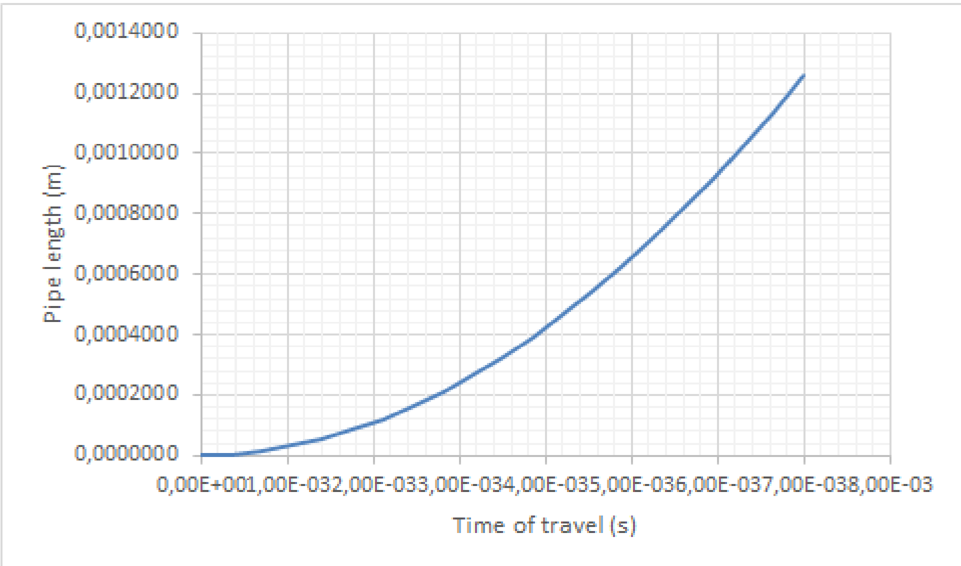


Figure 8.7: Time of travel shore grade 75 – ANSYS result

c) Time of travel for shore grade 85 at 20 °C

Shore grade 85 at 20 °C	
Time (s)	Distance (m)
1,18E-38	0,0000000
3,50E-04	0,0000043
7,00E-04	0,0000152
1,05E-03	0,0000318
1,40E-03	0,0000541
1,75E-03	0,0000833
2,10E-03	0,0001202
2,45E-03	0,0001623
2,80E-03	0,0002105
3,15E-03	0,0002654
3,50E-03	0,0003267
3,85E-03	0,0003931
4,20E-03	0,0004649
4,55E-03	0,0005434
4,90E-03	0,0006279
5,25E-03	0,0007175
5,60E-03	0,0008123
5,95E-03	0,0009133
6,30E-03	0,0010207
6,65E-03	0,0011333
7,00E-03	0,0012516

Table 8.3: Time of travel shore grade 85 – ANSYS result

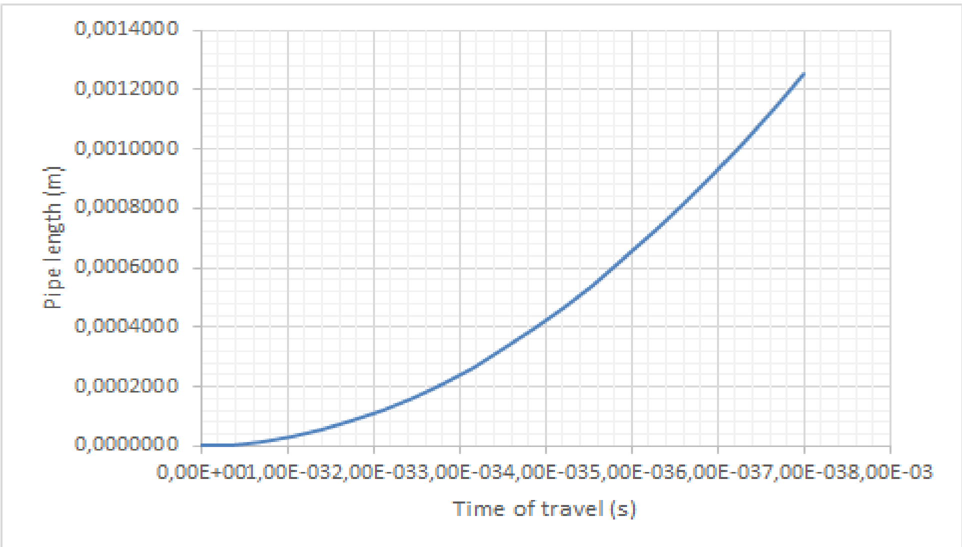


Figure 8.8: Time of travel shore grade 85 – ANSYS result

8.2.2 Time of travel of shore grade 65, 75 and 85 pig-Field test result

The time travel of each pig from the launcher end to the receiver end were recorded, Easyview software was used to record the time, taken for each pig. The results are shown in Table 8.4: Time of travel shore grade 65 field test–Table 8.6: Time of travel shore grade 85 field test

Shore grade 65 pig time of travel			
Test	Start time	Finish time	Total time
Test 1 forward movement	13:39:20	13:40:34	00:01:14
Test 1 backward movement	13:40:45	13:42:00	00:01:15
Test 2 forward movement	13:43:00	13:44:14	00:01:14
Test 2 backward movement	13:44:25	13:45:39	00:01:14
Test 3 forward movement	13:46:00	13:47:14	00:01:14
Test 3 backward movement	13:47:25	13:48:40	00:01:15
Test 4 forward movement	13:48:50	13:50:04	00:01:14
Test 4 backward movement	13:50:20	13:51:35	00:01:15
Test 5 forward movement	13:51:20	13:52:35	00:01:15
Test 5 backward movement	13:53:10	13:54:24	00:01:14
Test 6 forward movement	13:54:45	13:56:00	00:01:15
Test 6 backward movement	13:56:15	13:57:29	00:01:14

Table 8.4: Time of travel shore grade 65 field test

Shore grade 75 pig time of travel			
Test	Start time	Finish time	Total time
Test 1 forward movement	10:51:50	10:53:05	00:01:15
Test 1 backward movement	10:53:50	10:55:05	00:01:15
Test 2 forward movement	10:55:35	10:56:50	00:01:15
Test 2 backward movement	10:57:15	10:58:30	00:01:15
Test 3 forward movement	10:58:50	11:00:06	00:01:16
Test 3 backward movement	11:00:15	11:01:30	00:01:15
Test 4 forward movement	11:02:10	11:03:25	00:01:15
Test 4 backward movement	11:03:20	11:04:35	00:01:15
Test 5 forward movement	11:05:00	11:06:15	00:01:15
Test 5 backward movement	11:06:30	11:07:45	00:01:15
Test 6 forward movement	11:07:52	11:09:05	00:01:13
Test 6 backward movement	13:56:15	13:57:32	00:01:17

Table 8.5: Time of travel shore grade 75 field test

Shore grade 85 pig time of travel			
Test	Start time	Finish time	Total time
Test 1 forward movement	12:31:30	12:32:46	00:01:16
Test 1 backward movement	12:33:10	12:34:26	00:01:16
Test 2 forward movement	12:34:45	12:36:00	00:01:15
Test 2 backward movement	12:36:20	12:37:35	00:01:15
Test 3 forward movement	12:38:00	12:39:16	00:01:16
Test 3 backward movement	12:39:35	12:40:50	00:01:15
Test 4 forward movement	12:41:15	12:42:30	00:01:15
Test 4 backward movement	12:42:50	12:44:05	00:01:15
Test 5 forward movement	12:44:25	12:45:40	00:01:15
Test 5 backward movement	12:46:00	12:47:15	00:01:15
Test 6 forward movement	12:47:37	12:48:55	00:01:17
Test 6 backward movement	12:49:18	12:50:35	00:01:17

Table 8.6: Time of travel shore grade 85 field test

From Table 8.1 - Table 8.3 show the result of explicit dynamic results of shore grade 65, 75 and 85 pig time of travel from one end to the other. A section of the 12m test rig was model and extrapolation was used to arrive at the total time of 12m test rig this was done due to the ANSYS limited capacity.

Also, Table 8.4 - Table 8.6 show the result of time of travel from one end to the other end of 12m rig. Easy View, was used to record the time of travel for shore grade 65, 75 and 85.

The result of ANSYS corresponds to that of Easy-view. Both result show that shore grade 65 takes less time, follow by shore grade 75 and lastly shore grade 85. It is observed that shore grade 85 took more time, 1.15second. This is due to its high stiffness, which serves as a resistance to motion keeping all condition constant. This implies that if speed is a concern at temperature 10 °C -20 °C, then shore grade 65 should be used. Since the test was conducted in this temperature range and also the temperature has effect in shore grade material behaviour.

8.2.3 Transient dynamic result of shore grade 65, 75 and 85

One of the major objectives of this thesis work is to generate transient dynamic models for shore 65, 75 and 85 at 20 °C with finite element analysis in order to determine the deflection and reaction forces experience by the polyurethane and the pipe wall during transient dynamic conditions. Below are the ANSYS results of deflection and reaction forces.

8.2.3.1 Deflection

The deflection of shore grade 65, 75 and 85 at a temperature of 20 °C is shown below. It is observed that the deflection is almost typical for the differential pressure application and with temperature increase.

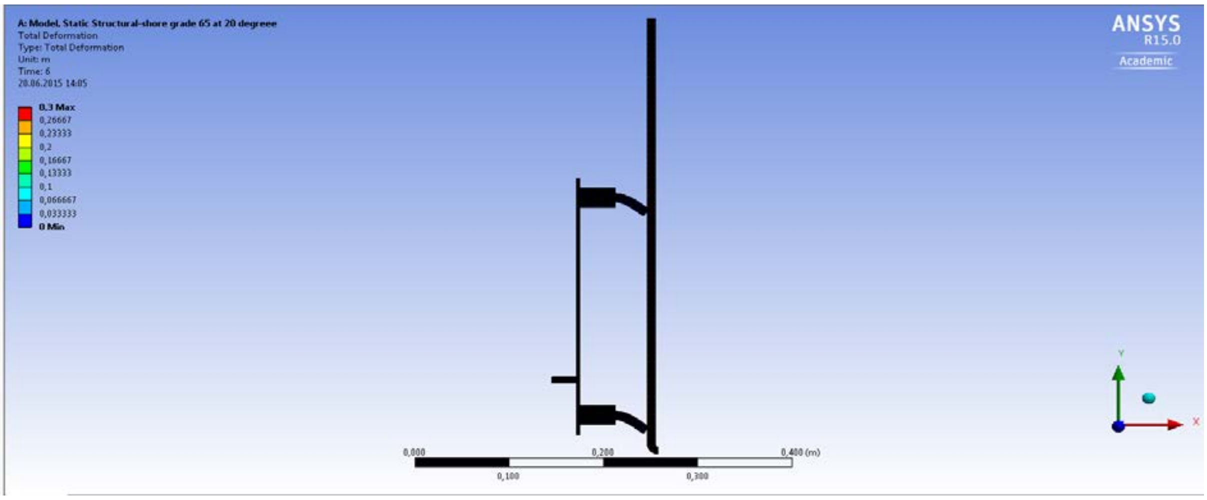


Figure 8.9: PU deflection - transient dynamic

8.2.3.2 Transient dynamic reaction forces of shore grade 65, 75 & 85 at 20 °C

Figure 8.10: Dynamic Reaction forces of shore grade 65, 75 and 85 at 20 °C shows the plot of shore grade 65, 75 and 85 at 20 °C which is one of the objective of this thesis.

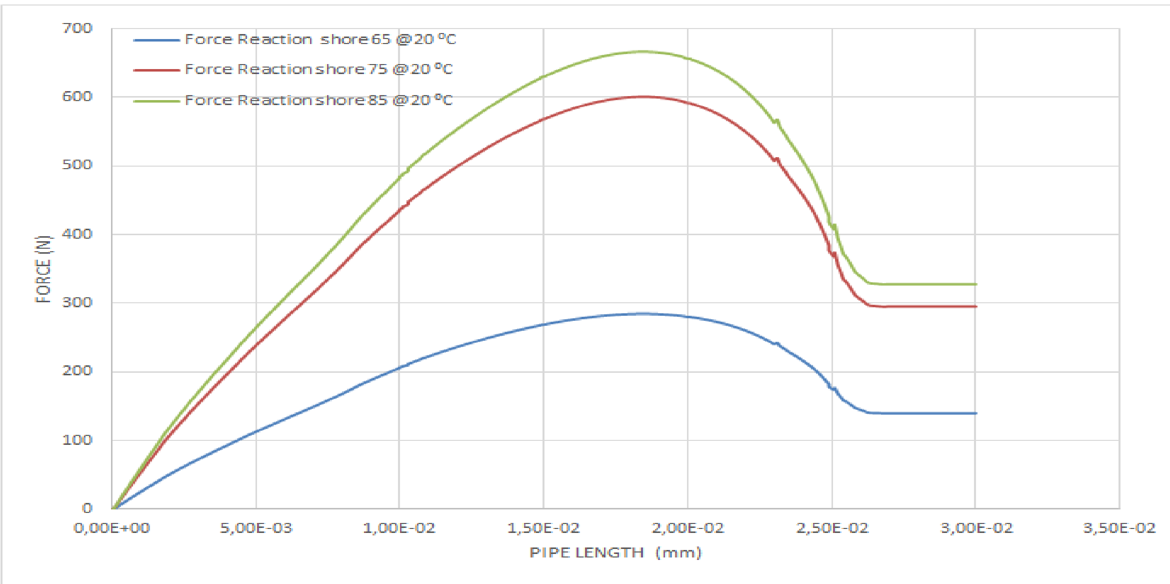


Figure 8.10: Dynamic Reaction forces of shore grade 65, 75 and 85 at 20 °C

8.2.3 Resultant force for shore grade 65, 75 and 85 -Validation

Field test was carried out in IK AS facility in Forus. The test involves testing shore grade 65, 75 and 85 pig in a 30mm test rig. A pull test was carried out at 10 °C, these show the force experience by the seal/ disc of pig during pigging operations. The pull test result are shown in Table 8.7-Table 8.9 in comparison with ANSYS result at temperature of 20 °C.

Figure 8.11: Shore grade 65 Figure 8.12: Shore grade 75 Figure 8.13: Shore grade 85

a) Pull test result (Field test result) and ANSYS result- Resultant force

Pull test resultant force at 10 °C		ANSYS resultant force at 20 °C
Test 1	355N	280N
Test 2	350N	280N
Test 3	355N	280N

Table 8.7: Shore grade 65, Pull test and ANSYS result

Pull test resultant force at 10 °C		ANSYS resultant force at 20 °C
Test 1	615N	600N
Test 2	610N	600N
Test 3	600N	600N

Table 8.8: Shore grade 75, Pull test and ANSYS result

Pull test resultant force at 10 °C		ANSYS resultant force at 20 °C
Test 1	895N	670N
Test 2	870N	670N
Test 3	860N	670N

Table 8.9: Shore grade 85, Pull test and ANSYS result

In summary, the transient dynamic analysis of shore grade 65, 75 and 85 were investigated at temperature of 20 °C. This was achieved by mapping the stress-strain data of material property into model and also the application of differential pressure on the pig disc in order to drive it into the 8’’ pipe. The time it takes for the pig to travel from one section of the model pipe was recorded. Also the deflection, kinetic reaction forces on the wall was recorded.

A field test was conducted in IK AS facilities Forus. It involves investigating the time it takes for the pig to travel from one end to the other of the 8’’x 12m long test rig. In addition, another field test was carried out with shore grade 65, 75 and 85 at 10 °C, the resultant force of shore grade 65, 75 and 85 was recorded.

In both cases, the ANSY and field test result on the time of travel from one end to the other end are almost same. With that of field test slightly higher. Also shown is that the lowest time of travel is that of shore grade 65 pig discs and that of shore grade 85 the highest. This is due to the increase in stiffness of the shore grade discs, hence the reduction of speed.

In addition, in comparison of the wall force between the PU and the pipewall, the field test result is almost same as that of ANSYS result. With the field test slightly higher. This is due to temperature of testing in the field. As temperature increase, the wall forces reduces due to strain, hence a slight reduction of reaction force of field test (pull test) as compare to the ANSYS result.

9. Conclusion

9.1 Conclusion, Recommendation and Further Work

9.1.1 Summary and Conclusion

Shore grade 65, 75 and 85 of polyurethane material were studied in this thesis. It was done for better understanding of the shore grade material behaviour. This is in accordance to the fact that different composition of polyurethane yield different behaviour. And at different temperature the behaviour of polyurethane differs also. During the life cycle of process transport facility, pig and pipeline are subjected to different operating temperatures, hence the study of different temperature and its effect on the material behaviour of polyurethane, which will in turn develop a deeper understanding of keeping pipeline as much as possible to its as-built condition. In another words, keeping maximum continuous flow as that of design state, this tends to reduce cost and increase the life span of pipeline.

9.1.2 Tensile test

The tensile test of the polyurethane (shore grade 65, 75 and 85) at different temperatures (20 ^{0}C, 40 ^{0}C, 60 ^{0}C, 70 ^{0}C and 80 ^{0}C) were carried out in accordance with the test standard for rubber (ASTMD412, 2013a). The stress-strain data of the material at the various temperature were obtained, which represent the material behaviour at the different temperature. The tensile test result shows that shore grades 65, 75 and 85 show similar stress-strain curves irrespective of temperature change. There are significant difference in the ultimate stress and the ultimate elongation. In most cases shore grade 85 has the highest ultimate stress and elongation while that of shore grade 65 and 75 interchange in ultimate stress and elongation due to temperature changes with shore 75 the higher in both. In addition, the effect of temperature is visible with shore grade 85 with the highest young modulus than that of shore 75 and 65 (Patel et al., 2008). And since the young modulus is directly related to the stiffness, this implies that shore grade 65, 75 and 85 experience changes in stiffness as a result of temperature increase. The tensile test further shows how the use of different ingredient in similar formula can result in some properties that are similar and others vary substantially. It also shows that successive stress produces strain until rapture after which the strain and stress goes to zero. The lowest tensile strength for shore grade 65 is 2 MPa at 20^{o}C, shore grade 75 is 3 MPa at 40^{o}C and shore grade 85 is 4 MPa at 60^{o}C.

Finally during the tensile test, about 98% of the shore grade specimen tested during the tensile test break/fail, before the shoulder of the specimen and seldomly along the specimen length. This is due to strain concentration. Stress concentration and manufacturer errors would have led to failure at the shoulder region or inconsistency in the failure/break pattern, which was not the case of tensile test result. While the 2% failure were due to material and manufacture failure.

9.1.3 Model – Static Analysis of Shore grade 65, 75 and 85

The static analysis of shore grade 65, 75 and 85 were investigated for different operating temperatures (20 °C, 40 °C, 60 °C, 70 °C, and 80 °C). This was achieved by the application of step incremental displacement on the pig discs which drive the discs into the fixed 8’’ pipeline. This is to generate the static behaviour of pig of shore grade 65, 75, & 85 discs at the different temperatures.

The effect of temperatures changes on the reaction forces between the shore grade 65, 75 and 85 and pipeline wall was noted. It was observed with shore grade 85 that the increase in temperature result to lower reaction forces on the shore grade which is due to increase in strain experience by shore grade 85 as temperature increase. Similarly, shore grade 65 and 75 experience decrease in reaction forces on the pipeline wall due to temperature increase. In addition the reaction force on shore grade 85 is higher than shore 65, and 75 due to the higher stiffness of shore grade 85.

In addition, shore grade 65 at 70°C experiences the least contact (reaction) force, this is due to the fact that maximum strain occur at that temperature, and at that temperature (70°C) is suitable for pigging operation for shore grade 65. While shore 75 is suitable for pigging operation at 60°C due to the least contact (reaction) force as a result of strain. In addition, shore 85 is suitable for pigging at 80°C also due to reduced reaction force between PU and pipe wall.

9.1.4 Model - Transient dynamic Analysis of shore 65, 75 and 85

The transient dynamic analysis of shore grade 65, 75 and 85 were investigated at temperature of 20 ^{o}C. This was achieved by mapping the stress-strain data of material property into model and also the application of differential pressure 0.2bar on the pig disc (shore grade 65, 75 and 85) in order to drive it into the 8’’ pipeline. The time it takes for the pig to travel from one section of the model pipe was recorded. Also the deflection, kinetic reaction forces on the wall was recorded.

A field test was conducted in IK AS facilities Forus. It involves investigating the time it takes for the pig to travel from one end to the other of the 8''x 12m long test rig. In addition, another field test was carried out with pig of shore grade 65, 75 and 85 at 10 ^oC, the resultant force of shore grade 65, 75 and 85 was recorded.

In both cases, the ANSY and field test result on the time of travel from one end to the other end are almost same. With that of field test slightly higher. Also shown is that the lowest time of travel is that of shore grade 65 pig discs and that of shore grade 85 recorded the highest time of travel. This is due to the high stiffness of the shore grade 85 discs, hence the reduction of speed. In comparison of the wall force between the PU and the pipewall, the field test result is almost same as that of ANSYS. With the field test slightly higher. This is due to temperature of testing in the field. As temperature increase, the wall forces reduces due to strain, hence a slight reduction of reaction force from ANSYS due to temperature difference.

9.2 Recommendation and further works

This thesis was based on the understanding of polyurethane material, shore grade 65, 75 and 85 used primary as an integrated part of pig design for pigging services of pipelines.

The study was extensive and intensive with a view to understand the behaviour of polyurethane material shore grade 65, 75 and 85 change with temperatures and the effect of these changes with regards with deflection and the reaction force with pipe wall.

In view of the above, the following are recommendations for further works that need to be considered.

- Material behaviour of other shore grades should be studied. Example are shore grade 60, 70, 80, 90 and 95.
- Critical study of the influence of pipeline coefficient of friction and/or surface roughness on the reaction forces.
- Shore grade discs studied should be extended to all pig-gable sizes and pipeline sizes.
- Computational fluid dynamic analyses tools should be incorporated to enable all fluid property adequately taken care of and fully analyzed.

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11. Appendix

Appendix 1 Constituent of Shore grade 65, 75 and 85

BAULÉ
a joint venture between Bayer MaterialScience AG and Michel Baulé SA

MDQ 45163 + D45MF + BDO

60 to 95 Shore A

NATURE OF COMPONENTS

Prepolymer nature	Nature of chain extender and other components	
MDI - Ester	D45MF	Ester formulated polyol
	BDO 1.4	Alcohol chain extender

CHARACTERISTICS OF COMPONENTS

	Unit	MDQ 45163	D45MF	BDO 1.4
% NCO	%	16.40 (± 0.2)	-	-
Physical appearance at room temperature	-	liquid	solid	solid
Processing temperature	℃	45	60	45
Viscosity at processing temperature	cps	600	1200	30
Specific gravity at processing temperature	-	1.17	1.15	1.01

CHARACTERISTICS

Properties

- Good abrasion and tear resistance,
- Good resistance to chemicals (hydrocarbons, oils, solvents…).

Comments

- Low processing temperature,
- Suitable for applications such as screens, scrapers, pigs, concrete blades, sheets, vibratory bowls…
- Mercury free quasi MDI technology,

ELASTOMER TYPICAL PROPERTIES (DATA GIVEN AS AN INDICATION)

Prepolymer			MDQ 45163							
Chain extender			D45MF + BDO 1.4							
Hardness at 20℃	DIN 53505	Shore	60 A	65 A	70 A	75 A	80 A	85 A	90 A	95 A
10% Modulus	DIN 53504	MPa	0.5	0.6	0.7	0.9	1.3	2.1	3.4	6.0
100% Modulus	DIN 53504	MPa	2.1	2.6	3.1	3.9	5.0	7.0	9.9	13.8
200% Modulus	DIN 53504	MPa	3.1	3.9	4.8	6.2	7.8	10.7	14	17.7
300% Modulus	DIN 53504	MPa	4.4	5.6	7.0	9.1	11	14.8	18.9	21.5
Tensile strength	DIN 53504	MPa	36	41	46	51	63	47	45	37
Elongation at break	DIN 53504	%	565	560	540	535	535	530	520	510
Tear strength : without nick	ISO 34-1	kN/m	46	56	63	74	87	106	124	142
Tear strength : with nick	ISO 34-1	kN/m	20	22	25	27	30	38	46	72
Resilience	DIN 53512	%	45	42	39	38	30	30	33	36
Abrasion loss	ISO 4649	mm³	30	30	30	30	30	40	40	40
Compression set (deflection / 22 h / 70 ℃)	ISO 815-1	%	16	17	17	18	18	20	23	31
Hardness at -5℃	DIN 53505	Shore	64 A	68 A	74 A	78 A	84 A	90 A	95 A	99 A
Hardness at 80℃	DIN 53505	Shore	56 A	61 A	65 A	70 A	75 A	83 A	89 A	95 A
Specific gravity			1.21	1.21	1.21	1.21	1.21	1.22	1.23	1.24

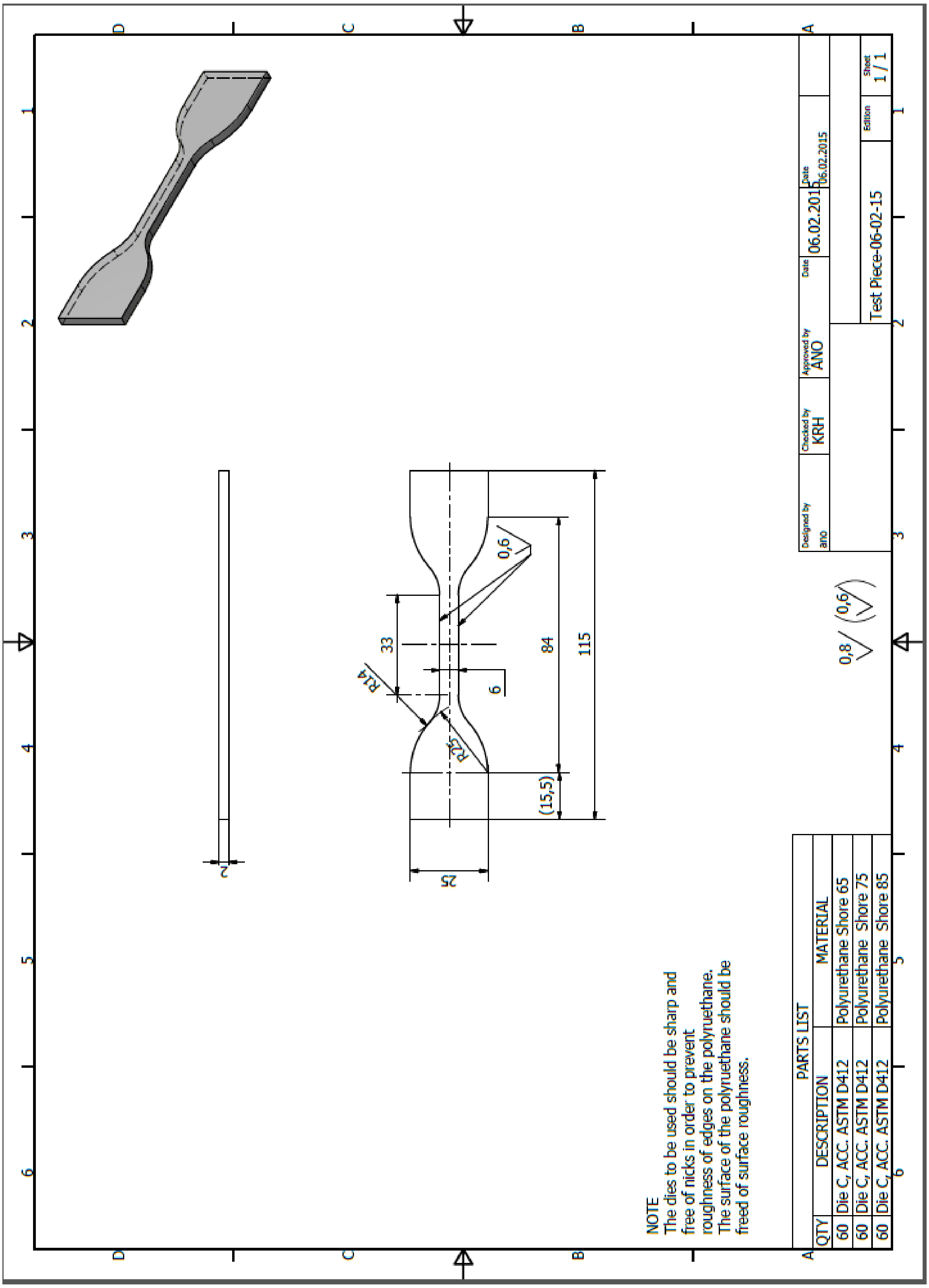
Labelling : This system data sheet is only valid in combination with the corresponding components current safety data sheets ! Any updating of safety relevant information – in accordance with EU directives – will only be reflected in the Safety Data Sheets, copies of which will be revised and distributed. For further technical information relating to safety, the Safety Data Sheets should be consulted.

BAULÉ - ZI - 46, avenue des Allobroges - BP 116 - 26103 Romans cedex - France - Tel. 33 (0)4 75 72 72 75 - Fax 33 (0)4 75 02 11 73 - E-mail : info@baule.com - www.baule.com

05.02.10 | 00

BAULÉ Systems Division is certified ISO 9001 : 2008

Appendix 2 Detailed dimension of die C



Appendix 3 Stress-strain data

shore 65 @20degree	
strain	stress
mm/mm	N/m^2
0	-67727,273
0,011920303	92424,2424
0,039115152	-31212,121
0,064523333	30757,5758
0,089780909	59545,4545
0,115031818	90606,0606
0,140286364	117121,212
0,165538485	143636,364
0,190791212	187121,212
0,216043939	213030,303
0,241296061	253030,303
0,266550606	284696,97
0,291802424	317727,273
0,317053636	343939,394
0,342305455	377727,273
0,367558182	405151,515
0,392811212	434696,97
0,418063939	463787,879
0,443315758	494545,455
0,468569697	526060,606
0,493822424	547575,758
0,519075152	570454,545
0,544327273	588333,333
0,56958	624848,485
0,594830909	642272,727
0,62008303	666969,697
0,645335758	692424,242
0,670588485	714545,455
0,695842424	736666,667
0,721095152	764545,455
0,746346061	792121,212
0,771600909	817727,273
0,796852727	838636,364
0,822104545	860757,576
0,847356667	883181,818
0,872607576	913030,303
0,897860303	934242,424
0,923114242	948939,394
0,94836697	983484,848
0,973619697	1008787,88
0,998872727	1027272,73
1,024125455	1050303,03
1,049377273	1071515,15
1,074629394	1092878,79
1,099882121	1126212,12
1,125133939	1132727,27
1,150385152	1166515,15
1,175638788	1183181,82
1,200891515	1217121,21

shore 75 @20degree	
strain	stress
mm/mm	N/m^2
0	-71515,15
0,011905	81515,152
0,03912	-15454,55
0,06453	47878,788
0,089788	93333,333
0,11504	146818,18
0,140293	189848,48
0,165546	232878,79
0,190799	282878,79
0,216052	318939,39
0,241304	361969,7
0,266556	405909,09
0,291808	440757,58
0,31706	469393,94
0,342312	500606,06
0,367566	536818,18
0,392819	561363,64
0,418072	596363,64
0,443324	617272,73
0,468576	637272,73
0,49383	662575,76
0,519082	688181,82
0,544334	704242,42
0,569586	732424,24
0,594838	753333,33
0,620091	766969,7
0,645344	790454,55
0,670596	805757,58
0,695849	831363,64
0,721102	851969,7
0,746355	869242,42
0,771608	885000
0,796859	910303,03
0,822111	922272,73
0,847363	947424,24
0,872614	959696,97
0,897869	984393,94
0,923122	997121,21
0,948375	1018939,4
0,973627	1036666,7
0,99888	1055606,1
1,024132	1073636,4
1,049385	1087878,8
1,074638	1108787,9
1,099888	1128030,3
1,125141	1145454,5
1,150394	1172575,8
1,175646	1190000
1,2009	1204697

shore 85 @20degree	
strain	stress
mm/mm	N/m^2
0	-86515,152
0,0119418	73636,364
0,0391318	4090,9091
0,0645406	102727,27
0,0897982	163636,36
0,1150509	223636,36
0,1403024	302878,79
0,1655548	354696,97
0,1908067	420757,58
0,2160609	470909,09
0,2413127	517121,21
0,2665652	570606,06
0,2918188	605909,09
0,3170712	640606,06
0,3423239	681060,61
0,3675761	712272,73
0,3928276	739393,94
0,4180803	757272,73
0,4433321	787121,21
0,4685852	815606,06
0,4938382	839090,91
0,5190903	856969,7
0,5443445	880303,03
0,5695958	906363,64
0,5948488	918636,36
0,6201015	942727,27
0,6453533	965303,03
0,6706058	988636,36
0,6958579	1002727,3
0,7211097	1022121,2
0,746363	1046818,2
0,7716158	1060909,1
0,7968691	1083787,9
0,8221215	1094848,5
0,8473739	1118030,3
0,8726282	1140909,1
0,8978782	1151515,2
0,9231309	1177727,3
0,9483827	1192424,2
0,9736352	1214545,5
0,9988882	1234848,5
1,0241412	1249848,5
1,0493936	1268636,4
1,0746467	1280606,1
1,0998994	1306666,7
1,1251527	1318484,8
1,1504045	1339393,9
1,1756555	1355151,5
1,2009094	1375454,5

shore 65 @ 40degree	
strain	stress
mm/mm	N/m^2
0	-55151,52
0,01189	99545,455
0,0391	-20303,03
0,064514	31060,606
0,089772	64696,97
0,115026	98333,333
0,140279	130909,09
0,165531	160000
0,190783	188939,39
0,216036	214545,45
0,241287	253636,36
0,266539	283030,3
0,291792	311666,67
0,317044	339090,91
0,342298	368181,82
0,36755	401515,15
0,392804	429545,45
0,418057	455000
0,443308	480909,09
0,46856	510303,03
0,493813	538181,82
0,519065	561212,12
0,544318	587878,79
0,56957	614696,97
0,594823	635303,03
0,620076	670757,58
0,645328	686060,61
0,670581	713636,36
0,695834	743484,85
0,721086	766515,15
0,746338	794848,48
0,771591	811969,7
0,796842	843636,36
0,822095	863333,33
0,847348	892878,79
0,872601	911818,18
0,897854	930757,58
0,923107	958939,39
0,948358	986818,18
0,973612	1011212,1
0,998863	1033333,3
1,024115	1051212,1
1,049368	1082121,2
1,07462	1100303
1,099874	1125303
1,125126	1147878,8
1,150378	1174545,5
1,175632	1205000
1,200885	1222727,3

1,226144545	1231363,64
1,251397273	1257272,73
1,276650909	1279848,48
1,30190303	1305606,06
1,327155758	1327424,24
1,352408485	1347575,76
1,377658788	1372121,21
1,402911515	1401363,64
1,428163333	1423787,88
1,453416364	1445606,06
1,47867	1471666,67
1,503921818	1489090,91
1,529174848	1507272,73
1,554428485	1538030,3
1,579681212	1556818,18
1,604934242	1578181,82
1,630185152	1609090,91
1,655436061	1636969,7
1,68069	1657121,21
1,705941818	1680303,03
1,731194545	1699393,94
1,756448485	1725909,09
1,781700303	1748939,39
1,80695303	1778030,3
1,832206061	1794545,45
1,857458788	1815606,06
1,882710606	1836515,15
1,907962727	1855757,58
1,933214545	1880606,06
1,958466364	1898181,82
1,983720303	1920757,58
2,008973939	1932121,21
2,034225758	1943636,36
2,059477879	1951666,67
2,084731515	1972727,27
2,109984242	1975000
2,135236364	1987424,24
2,142054545	1111666,67
2,143569394	317121,212
2,145084242	-484242,42
2,146852424	-1307424,2
2,149125455	-2106060,6
2,153921212	-2878484,8
2,179174242	-2751363,6
2,204427879	-2757575,8
2,229679697	-2760606,1
2,254932727	-2754242,4
2,280186364	-2754242,4
2,305438485	-2752878,8
2,330692121	-2762121,2
2,35594303	-2756969,7
2,381193939	-2758787,9

1,226151	1224545,5
1,251405	1236515,2
1,276658	1262878,8
1,30191	1268333,3
1,327163	1292424,2
1,352414	1319242,4
1,377665	1323484,8
1,402919	1353181,8
1,428172	1371060,6
1,453425	1389697
1,478678	1405303
1,503929	1423787,9
1,529183	1443939,4
1,554436	1460000
1,579688	1479393,9
1,60494	1502424,2
1,630191	1516212,1
1,655444	1540909,1
1,680697	1560000
1,70595	1574545,5
1,731203	1592272,7
1,756455	1614848,5
1,781708	1633030,3
1,806961	1649545,5
1,832214	1663030,3
1,857465	1688484,8
1,882717	1700454,5
1,90797	1722272,7
1,933221	1751363,6
1,958474	1759545,5
1,983729	1773030,3
2,008981	1806969,7
2,034233	1818939,4
2,059485	1841363,6
2,084738	1860000
2,109991	1872727,3
2,135243	1890303
2,160494	1912272,7
2,185747	1937424,2
2,210999	1960303
2,236253	1967727,3
2,261506	1988333,3
2,286758	2010454,5
2,312011	2032272,7
2,337264	2048181,8
2,362517	2060757,6
2,387768	2090151,5
2,413019	2103636,4
2,438272	2123181,8
2,463525	2150454,5
2,488778	2167575,8
2,514031	2182727,3

1,2261603	1399393,9
1,251413	1409545,5
1,2766664	1431969,7
1,3019194	1447424,2
1,3271721	1457272,7
1,3524245	1488636,4
1,3776773	1500757,6
1,4029297	1521515,2
1,4281821	1541363,6
1,4534339	1560757,6
1,4786855	1571060,6
1,5039382	1595454,5
1,5291915	1615454,5
1,5544442	1634090,9
1,5796973	1657878,8
1,6049497	1672575,8
1,6302024	1699090,9
1,6554552	1716060,6
1,6807073	1728333,3
1,7059591	1743484,8
1,7312109	1761212,1
1,7564642	1783181,8
1,7817161	1807121,2
1,8069685	1827878,8
1,8322218	1844393,9
1,8574752	1863181,8
1,8827276	1880757,6
1,9079803	1907575,8
1,9332321	1924393,9
1,9584852	1941060,6
1,9837355	1964393,9
2,0089894	1990000
2,0342412	2006515,2
2,0594936	2019848,5
2,0847473	2035454,5
2,1100003	2055000
2,1352527	2078939,4
2,1605055	2095606,1
2,1857582	2119393,9
2,2110106	2135000
2,2362615	2168181,8
2,2615136	2178484,8
2,2867664	2205000
2,3120188	2216969,7
2,337273	2244848,5
2,3625255	2258181,8
2,3877782	2275454,5
2,4130306	2300151,5
2,438283	2323484,8
2,4635358	2337727,3
2,4887876	2357121,2
2,5140397	2381363,6

1,226136	1253787,9
1,251389	1278939,4
1,27664	1301515,2
1,301894	1328181,8
1,327146	1358636,4
1,352398	1375454,5
1,377651	1396060,6
1,402904	1442272,7
1,428158	1461515,2
1,45341	1481060,6
1,478662	1508939,4
1,503915	1538939,4
1,529166	1560909,1
1,554419	1588181,8
1,579671	1620454,5
1,604923	1646212,1
1,630176	1668787,9
1,65543	1695454,5
1,680682	1723787,9
1,705934	1752727,3
1,731187	1772727,3
1,756441	1807878,8
1,781691	1833030,3
1,806944	1860909,1
1,832197	1883181,8
1,857448	1920303
1,882702	1935606,1
1,907953	1975909,1
1,933207	2004393,9
1,958461	2034545,5
1,983713	2057878,8
2,008965	2087727,3
2,034218	2119090,9
2,059469	2145151,5
2,084722	2165000
2,109974	2195151,5
2,135227	2231363,6
2,160479	2258939,4
2,185732	2287272,7
2,210985	2325303
2,236238	2351515,2
2,26149	2386515,2
2,286742	2421969,7
2,311995	2452272,7
2,337247	2478636,4
2,362499	2509848,5
2,387752	2546818,2
2,413005	2579848,5
2,438256	2608333,3
2,463511	2644545,5
2,488763	2676818,2
2,514017	2705757,6

2,40644697	-2758787,9
2,431698788	-2756666,7
2,456952424	-2757575,8
2,482205455	-2750000
2,507457273	-2755151,5
2,532711212	-2757878,8
2,557964848	-2738939,4
2,583215758	-2755454,5
2,600133636	-2755000

2,539284	2204848,5
2,564536	2217575,8
2,589788	2241969,7
2,615042	2257575,8
2,640293	2278787,9
2,665546	2296818,2
2,690798	2316969,7
2,716049	2340303
2,741303	2364242,4
2,766555	2375909,1
2,791809	2395757,6
2,817062	2423636,4
2,842313	2439697
2,867567	2453030,3
2,89282	2474697
2,918071	2500151,5
2,943323	2520909,1
2,968575	2536515,2
2,993827	2555909,1
3,019081	2580000
3,044333	2600909,1
3,069586	2625757,6
3,094839	2646818,2
3,120092	2660303
3,145344	2691515,2
3,170596	2704848,5
3,195849	2729697
3,2211	2748939,4
3,246353	2778636,4
3,271606	2800151,5
3,296858	2825303
3,322112	2832575,8
3,347364	2849545,5
3,372617	2877121,2
3,39787	2903030,3
3,423123	2924393,9
3,448375	2945909,1
3,473625	2972121,2
3,498878	2996363,6
3,524131	3018484,8
3,549384	3043484,8
3,574638	3064393,9
3,59989	3081515,2
3,625142	3109697
3,650395	3128030,3
3,675647	3160151,5
3,7009	3170151,5
3,726152	3196060,6
3,751403	3226515,2
3,776656	3247878,8
3,801909	3268181,8
3,827162	3292272,7

2,5392915	2398787,9
2,5645433	2436363,6
2,5897973	2443181,8
2,6150509	2468333,3
2,6403027	2488787,9
2,6655567	2502575,8
2,6908085	2523181,8
2,7160612	2545000
2,7413142	2573333,3
2,7665652	2596969,7
2,791817	2612121,2
2,81707	2638787,9
2,8423218	2654848,5
2,8675755	2676969,7
2,8928285	2699848,5
2,9180803	2719090,9
2,9433339	2739545,5
2,968587	2763181,8
2,9938388	2785606,1
3,0190906	2799545,5
3,0443436	2821818,2
3,0695936	2848181,8
3,0948473	2867878,8
3,1201003	2899090,9
3,1453539	2914242,4
3,1706067	2934393,9
3,1958579	2958787,9
3,2211115	2982121,2
3,2463642	3012575,8
3,2716164	3023181,8
3,2968691	3053939,4
3,32212	3066212,1
3,3473709	3092575,8
3,3726267	3121969,7
3,3978785	3147727,3
3,4231315	3164090,9
3,4483842	3190757,6
3,4736361	3202878,8
3,49889	3228787,9
3,5241418	3252121,2
3,5493936	3268787,9
3,5746467	3290000
3,5998976	3325000
3,6251503	3345000
3,6504033	3355606,1
3,675657	3384090,9
3,7009088	3410757,6
3,7261618	3439545,5
3,7514145	3453787,9
3,7766664	3476212,1
3,8019194	3496212,1
3,8271712	3516515,2

2,539268	2737575,8
2,564521	2770151,5
2,589772	2808636,4
2,615023	2848636,4
2,640277	2873787,9
2,665529	2908181,8
2,690781	2942272,7
2,716037	2977575,8
2,741288	3013181,8
2,766542	3035000
2,791793	3071818,2
2,817045	3100909,1
2,842299	3137121,2
2,867549	3171969,7
2,892802	3210909,1
2,897854	2415909,1
2,899116	1618787,9
2,900379	753484,85

3,852415	3317121,2
3,877667	3340757,6
3,90292	3356818,2
3,928173	3386515,2
3,953425	3415606,1
3,978678	3433181,8
4,003929	3459393,9
4,029181	3491212,1
4,054433	3510909,1
4,079688	3530454,5
4,10494	3553636,4
4,130192	3579848,5
4,155445	3611818,2
4,180698	3624848,5
4,20595	3654545,5
4,219586	2815000
4,220848	1980303
4,222111	1078636,4
4,223373	207575,76

3,852423	3549242,4
3,8776761	3568939,4
3,9029279	3583333,3
3,9281815	3613181,8
3,9534355	3620606,1
3,9786864	3647727,3
4,0039391	3678636,4
4,029193	3688030,3
4,0544439	3712424,2
4,0796967	3731212,1
4,1049476	3755606,1
4,1302006	3779393,9
4,1554533	3795000
4,1807064	3818484,8
4,20596	3835909,1
4,2312127	3855000
4,2564648	3879545,5
4,2817176	3904393,9
4,3069703	3927121,2
4,3322224	3944545,5
4,3574752	3963484,8
4,3827252	3991515,2
4,4079779	3998484,8
4,4332318	4030606,1
4,4584855	4045606,1
4,4837376	4063787,9
4,5089903	4090151,5
4,534243	4111515,2
4,5594952	4136363,6
4,5847488	4161818,2
4,6099997	4177272,7
4,6352518	4197727,3
4,6605036	4225303
4,6857564	4245757,6
4,7110103	4268030,3
4,7362621	4293484,8
4,7615148	4315606,1
4,7867688	4343484,8
4,8120197	4370000
4,8372733	4383484,8
4,8625255	4411969,7
4,8877773	4439697
4,9130291	4461969,7
4,9382821	4475303
4,9635348	4510151,5
4,9706048	3591212,1
4,9718679	2664393,9
4,9728779	1858333,3
4,9738876	1062424,2
4,9751509	140757,58

shore 75 @40degree	
strain	stress
mm/mm	N/m²
0	-63939,39
0,011934	95454,55
0,039125	-10757,58
0,064531	52424,24
0,089789	99393,94
0,115042	142878,8
0,140293	179697
0,165546	228787,9
0,190799	270909,1
0,216052	301060,6
0,241305	340000
0,266556	366666,7
0,29181	397878,8
0,317064	438636,4
0,342314	464697
0,367567	487272,7
0,392819	510000
0,418072	539393,9
0,443324	560303
0,468577	586515,2
0,49383	608787,9
0,519083	630454,5
0,544335	651515,2
0,569588	674242,4
0,59484	694848,5
0,620092	723030,3
0,645345	736060,6
0,670597	755606,1
0,695849	780909,1
0,721102	796212,1
0,746356	820000
0,771607	844545,5
0,79686	849697
0,822113	874393,9
0,847365	890303
0,872619	910000
0,89787	928484,8
0,923122	946666,7
0,948375	972727,3
0,973626	985909,1
0,99888	1005303
1,024134	1026212
1,049386	1036970
1,074638	1058485
1,099891	1075303
1,125143	1100758
1,150395	1116212
1,175647	1134242
1,200899	1155303

shore 85 @40degree	
strain	stress
mm/mm	N/m²
0	-81515,15
0,011931	92878,79
0,03913	24848,48
0,064536	114242,4
0,089794	178939,4
0,115047	241363,6
0,140299	313333,3
0,165552	358484,8
0,190803	429697
0,216056	486969,7
0,241308	532424,2
0,266562	576818,2
0,291814	624242,4
0,317067	655151,5
0,342319	692727,3
0,367573	732272,7
0,392825	752727,3
0,418077	787121,2
0,443329	815000
0,468581	840454,5
0,493833	864242,4
0,519085	887575,8
0,544339	910000
0,569592	928939,4
0,594845	958030,3
0,620098	983030,3
0,64535	1002576
0,670602	1013636
0,695855	1041061
0,721106	1061667
0,746359	1087576
0,771611	1104848
0,796865	1134545
0,822117	1154394
0,84737	1168333
0,872622	1192273
0,897876	1216667
0,923128	1232273
0,94838	1261212
0,973632	1282121
0,998884	1300303
1,024137	1313182
1,049389	1335455
1,074642	1355606
1,099894	1374394
1,125148	1393939
1,1504	1414697
1,175653	1435909
1,200905	1459091

Shore 65 @60degree		Shore 75 @60degree	
strain	stress	strain	stress
mm/mm	N/m²	mm/mm	N/m²
0	-43181,82	0	-50454,545
0,011964	112121,2	0,011919	93636,364
0,039144	-454,5455	0,039117	-12272,727
0,064553	43484,85	0,064529	61515,152
0,08981	66060,61	0,089788	100000
0,115062	89848,48	0,11504	132878,79
0,140315	119545,5	0,140292	178787,88
0,165567	146969,7	0,165546	211818,18
0,19082	168333,3	0,190797	258181,82
0,216073	191969,7	0,216049	293484,85
0,241325	217424,2	0,241302	327272,73
0,266578	234848,5	0,266555	356969,7
0,291831	268787,9	0,291807	388333,33
0,317084	283333,3	0,31706	421212,12
0,342337	309545,5	0,342312	447575,76
0,367588	328636,4	0,367566	466363,64
0,39284	353181,8	0,392819	492878,79
0,418093	382424,2	0,418071	518636,36
0,443344	388636,4	0,443322	521969,7
0,468598	420454,5	0,468575	537727,27
0,49385	432727,3	0,493827	550454,55
0,519103	454090,9	0,519079	555000
0,544357	472727,3	0,544332	557575,76
0,569609	490909,1	0,569586	572878,79
0,594862	513787,9	0,594838	584848,48
0,620114	532272,7	0,620091	607272,73
0,645365	554242,4	0,645343	619090,91
0,670617	571212,1	0,670597	638484,85
0,69587	589545,5	0,695848	657878,79
0,721123	595151,5	0,7211	673787,88
0,746376	619242,4	0,746352	686060,61
0,771628	620151,5	0,771604	706060,61
0,796882	641818,2	0,796858	721666,67
0,822134	662121,2	0,82211	744848,48
0,847386	677575,8	0,847363	751666,67
0,872639	688484,8	0,872616	777121,21
0,897892	704848,5	0,897868	799090,91
0,923143	723636,4	0,923122	815909,09
0,948396	739090,9	0,948374	828636,36
0,973648	757121,2	0,973625	843636,36
0,9989	782727,3	0,998878	866212,12
1,024154	796515,2	1,024129	886060,61
1,049407	820151,5	1,049382	907272,73
1,074659	830151,5	1,074636	923939,39
1,099912	849393,9	1,099889	938787,88
1,125165	875151,5	1,125141	957121,21
1,150416	897272,7	1,150395	971212,12
1,175668	922121,2	1,175645	989242,42
1,200919	933939,4	1,200899	1010757,6

1,226152	1177121
1,251405	1186061
1,276658	1214545
1,301912	1231667
1,327163	1245303
1,352416	1259545
1,377669	1283030
1,402921	1298030
1,428173	1314091
1,453425	1325000
1,478676	1349394
1,50393	1371818
1,529183	1386667
1,554436	1412273
1,579689	1427424
1,604941	1446061
1,630194	1471818
1,655446	1480455
1,680697	1509091
1,705951	1531515
1,731203	1539697
1,756455	1557273
1,781709	1580000
1,806961	1593030
1,832214	1617424
1,857466	1626970
1,882718	1655455
1,907971	1664697
1,933224	1688485
1,958476	1714697
1,983728	1730152
2,008979	1750000
2,034233	1763030
2,059486	1787879
2,084739	1800909
2,109992	1827576
2,135244	1852424
2,160497	1861515
2,185748	1881667
2,211001	1902879
2,236252	1921061
2,261505	1941970
2,286759	1956212
2,312011	1979091
2,337265	1997879
2,362517	2022121
2,387769	2047879
2,413022	2074091
2,438274	2081061
2,463526	2113030
2,48878	2130606
2,514031	2140606

1,226157	1483030
1,25141	1509394
1,276662	1525758
1,301914	1540303
1,327168	1572727
1,352421	1580303
1,377673	1613030
1,402925	1630758
1,428178	1653939
1,453432	1682273
1,478682	1693485
1,503935	1715152
1,529187	1738939
1,554439	1765303
1,579693	1793182
1,604945	1802576
1,630198	1825303
1,655451	1850758
1,680703	1879091
1,705956	1892727
1,731208	1915303
1,75646	1941061
1,781713	1967576
1,806965	1990455
1,832218	2008939
1,85747	2032879
1,882723	2056061
1,907977	2075000
1,933229	2106212
1,958481	2123636
1,983734	2150000
2,008986	2174848
2,034238	2190606
2,05949	2217424
2,084742	2247121
2,109996	2264242
2,135248	2296667
2,160501	2309091
2,185754	2341515
2,211008	2359091
2,236259	2375152
2,261511	2405152
2,286764	2423333
2,312015	2451212
2,337268	2471515
2,36252	2488636
2,387773	2520455
2,413027	2544091
2,43828	2571364
2,463532	2591970
2,488785	2617727
2,514035	2637727

1,226172	954242,4	1,226151	1031212,1
1,251426	968030,3	1,251403	1052272,7
1,276679	990454,5	1,276654	1068484,8
1,301932	1012273	1,301908	1074697
1,327185	1035909	1,327161	1099545,5
1,352436	1056212	1,352413	1112727,3
1,377691	1073485	1,377667	1142878,8
1,402941	1101667	1,402919	1156363,6
1,428194	1122576	1,428171	1169848,5
1,453446	1139394	1,453424	1194848,5
1,478698	1165758	1,478677	1210909,1
1,503951	1181515	1,503928	1235000
1,529204	1200606	1,529181	1244090,9
1,554457	1227727	1,554432	1266363,6
1,57971	1246364	1,579686	1292575,8
1,604963	1262727	1,604938	1303787,9
1,630215	1291364	1,630192	1325606,1
1,655468	1316364	1,655445	1341818,2
1,68072	1338333	1,680697	1366818,2
1,705972	1357879	1,70595	1380303
1,731223	1380303	1,731202	1402878,8
1,756475	1396061	1,756454	1418181,8
1,781728	1425303	1,781706	1444697
1,806983	1446364	1,806957	1463939,4
1,832235	1467121	1,832211	1476818,2
1,857488	1489394	1,857464	1506212,1
1,88274	1507273	1,882716	1517424,2
1,907992	1536970	1,90797	1533181,8
1,933246	1555909	1,933222	1563939,4
1,958498	1583333	1,958475	1583636,4
1,983748	1603333	1,983727	1599697
2,009001	1625455	2,00898	1621060,6
2,034255	1649242	2,034232	1648787,9
2,059506	1674091	2,059484	1660303
2,084761	1692879	2,084735	1681212,1
2,110012	1719848	2,109988	1708636,4
2,135266	1737879	2,135242	1721969,7
2,160518	1767424	2,160495	1745454,5
2,185771	1785000	2,185747	1755151,5
2,211022	1821667	2,211001	1781515,2
2,236275	1845000	2,236252	1810454,5
2,261526	1861818	2,261505	1827272,7
2,286778	1874394	2,286757	1854697
2,312032	1915152	2,312008	1864393,9
2,337285	1934242	2,337261	1888787,9
2,362538	1953939	2,362514	1912272,7
2,387791	1990758	2,387766	1922727,3
2,413042	2011212	2,41302	1949697
2,438296	2038182	2,438272	1965454,5
2,463549	2061970	2,463525	1990606,1
2,488799	2090758	2,488778	2017727,3
2,514052	2114545	2,51403	2031363,6

2,539282	2163333
2,564536	2176212
2,589789	2201364
2,615043	2226061
2,640295	2251818
2,665547	2275909
2,690801	2296818
2,716052	2321970
2,741304	2333939
2,766556	2348939
2,791807	2372424
2,817061	2392424
2,842315	2419545
2,867568	2445303
2,89282	2468333
2,918073	2480000
2,943325	2517879
2,968577	2539242
2,99383	2561364
3,019082	2582424
3,044334	2598182
3,069585	2626212
3,094838	2649091
3,120093	2682121
3,145345	2701212
3,170598	2720152
3,195851	2744394
3,221102	2766364
3,246355	2793939
3,271607	2817121
3,296858	2835455
3,322111	2866667
3,347364	2891061
3,372618	2913182
3,397871	2946970
3,423122	2955303
3,448375	2985758
3,473629	3015758
3,49888	3052727
3,524132	3070000
3,549385	3095152
3,574637	3124697
3,599888	3142424
3,625142	3166515
3,650395	3200758
3,675649	3226212
3,7009	3256515
3,721608	2422727
3,72287	1617424
3,724133	749848,5

2,539289	2651970
2,564541	2676818
2,589793	2697727
2,615046	2721818
2,640298	2746212
2,665552	2768030
2,690804	2788485
2,716056	2812879
2,74131	2835909
2,766562	2840000
2,791813	2870606
2,817067	2878182
2,842318	2897273
2,867572	2913788
2,892823	2930909
2,918077	2933788
2,943329	2946515
2,968583	2957273
2,993835	2968182
3,019087	2968939
3,044339	2973182
3,069591	2982273
3,094843	2984394
3,120096	2994697
3,145349	3015000
3,170601	3033333
3,195855	3059848
3,221107	3080303
3,246361	3111212
3,271613	3140303
3,296865	3168485
3,322118	3205758
3,347368	3232273
3,372622	3254697
3,397875	3296970
3,423126	3323485
3,44838	3354848
3,473633	3390303
3,498885	3411212
3,524138	3440000
3,549391	3465303
3,574642	3495000
3,599894	3521667
3,625146	3546212
3,650399	3577879
3,675652	3612727
3,700904	3644091
3,726158	3665606
3,75141	3691212
3,776663	3718333
3,801916	3739242
3,827168	3776061

2,539303	2144848	2,539283	2065151,5
2,564557	2160303	2,564535	2081969,7
2,58981	2193636	2,589787	2101818,2
2,615063	2224091	2,615038	2118484,8
2,640316	2251364	2,640291	2149545,5
2,665569	2283182	2,665545	2161818,2
2,690821	2308788	2,690798	2188636,4
2,716075	2330606	2,71605	2218333,3
2,741325	2353485	2,741303	2238787,9
2,766578	2393485	2,766555	2263030,3
2,79183	2408788	2,791807	2281212,1
2,817081	2446061	2,817059	2310909,1
2,842335	2478182	2,842313	2328333,3
2,867589	2501970	2,867564	2350303
2,892841	2536212	2,892816	2381060,6
2,918095	2564091	2,918071	2405606,1
2,943346	2595152	2,943322	2434848,5
2,968599	2628030	2,968575	2458181,8
2,993851	2646212	2,993828	2477272,7
3,019102	2680152	3,01908	2511666,7
3,044355	2716061	3,044333	2538333,3
3,069607	2747424	3,069585	2549545,5
3,09486	2783485	3,094838	2572272,7
3,120113	2804242	3,12009	2597424,2
3,145367	2832879	3,145341	2616969,7
3,170619	2876515	3,170595	2648333,3
3,183244	2005606	3,195849	2679848,5
3,184759	1089545	3,221101	2695909,1
3,186022	294242,4	3,246353	2728484,8
		3,271607	2754090,9
		3,296858	2767424,2
		3,322111	2801515,2
		3,347362	2823181,8
		3,372615	2854242,4
		3,397866	2885454,5
		3,42312	2900606,1
		3,448373	2924848,5
		3,473625	2950909,1
		3,498878	2986969,7
		3,524131	3004848,5
		3,549384	3038636,4
		3,574636	3065757,6
		3,599888	3091969,7
		3,625141	3112727,3
		3,650393	3139545,5
		3,675645	3164848,5
		3,700897	3193030,3
		3,72615	3230606,1
		3,751405	3246212,1
		3,776656	3276666,7
		3,801909	3312424,2
		3,827162	3334545,5

3,85242	3801818
3,877672	3820606
3,902924	3864394
3,928176	3884697
3,95343	3907576
3,978682	3939091
4,003935	3972727
4,029189	3996970
4,054442	4016970
4,079694	4035152
4,104945	4084242
4,130197	4103333
4,15545	4120000
4,180703	4155455
4,205955	4185455
4,231207	4215606
4,25646	4233788
4,281714	4256818
4,306966	4282879
4,332218	4306212
4,357471	4338182
4,382723	4362879
4,407975	4392424
4,433228	4424242
4,458481	4438788
4,483732	4471818
4,508985	4502121
4,534238	4523182
4,559491	4559242
4,584744	4585303
4,609997	4617273
4,635248	4649242
4,6605	4673939
4,685752	4710000
4,711006	4739545
4,736259	4769091
4,76151	4805152
4,786764	4834697
4,812016	4863939
4,837269	4897121
4,862522	4927273
4,887773	4956667
4,913026	4988182
4,938279	5026667
4,96353	5058636
4,988784	5088636
5,014035	5123939
5,039288	5155000
5,064541	5183939
5,089795	5214394
5,115048	5248333
5,140299	4858636

3,852413	3365454,5
3,877666	3396212,1
3,902918	3408484,8
3,928169	3438939,4
3,953423	3474545,5
3,978676	3506666,7
4,003929	3526060,6
4,029182	3561818,2
4,054433	3587575,8
4,079688	3619242,4
4,104939	3642424,2
4,130191	3668484,8
4,155444	3702121,2
4,180696	3728939,4
4,205948	3759697
4,231201	3781363,6
4,256454	3816515,2
4,281707	3834090,9
4,30696	3867424,2
4,332212	3890000
4,357464	3928939,4
4,382716	3959545,5
4,407969	3981060,6
4,43322	4009090,9
4,458473	4023939,4
4,483725	4060757,6
4,50898	4081818,2
4,534232	4107424,2
4,559485	4146666,7
4,584737	4165757,6
4,609989	4189393,9
4,635242	4205454,5
4,660494	4234242,4
4,685745	4264242,4
4,710998	4283333,3
4,715797	3476666,7
4,71706	2581212,1
4,71807	1791212,1
4,71908	998636,36
4,720344	72575,758

Shore 85 @60degree	
strain	stress
mm/mm	N/m²
0	-78030,303
0,011902	93030,303
0,039099	14545,4545
0,064507	108333,333
0,089764	163787,879
0,115017	223181,818
0,140268	287424,242
0,165521	347424,242
0,190773	414545,455
0,216027	454545,455
0,241279	516060,606
0,266532	554090,909
0,291785	597424,242
0,317038	634848,485
0,34229	663636,364
0,367542	701363,636
0,392794	736666,667
0,418046	760000
0,443299	786969,697
0,468551	821666,667
0,493805	848030,303
0,519057	874545,455
0,544311	894545,455
0,569563	919242,424
0,594815	943636,364
0,620068	977575,758
0,645319	989242,424
0,670572	1017272,73
0,695824	1033030,3
0,721076	1058181,82
0,74633	1077272,73
0,771583	1105454,55
0,796835	1130151,52
0,822088	1142424,24
0,84734	1170757,58
0,872593	1189242,42
0,897845	1210757,58
0,923096	1227121,21
0,948349	1253787,88
0,973602	1279090,91
0,998855	1302272,73
1,024108	1323181,82
1,04936	1352424,24
1,074613	1366515,15
1,099865	1393939,39
1,125118	1406363,64
1,15037	1433333,33
1,175622	1452575,76
1,200875	1480757,58

Shore 65 @70degree		Shore 75 @70degree		shore 85 @70degree	
strain	stress	strain	stress	strain	stress
mm/mm	N/m²	mm/mm	N/m²	mm/mm	N/m²
0	-30000	0	-55454,55	0	-65606,061
0,011942	112121,21	0,0119	92424,242	0,011915	91212,121
0,039129	-16060,61	0,039123	-6212,121	0,039113	11363,636
0,064538	40303,03	0,064533	40909,091	0,06452	101818,18
0,089797	58030,303	0,089793	92121,212	0,089778	150000
0,115048	92575,758	0,115045	130151,52	0,115029	206818,18
0,140301	107878,79	0,140298	170606,06	0,140281	281363,64
0,165552	131363,64	0,16555	210757,58	0,165535	333939,39
0,190804	157121,21	0,1908	253030,3	0,190787	383484,85
0,216058	187121,21	0,216053	296818,18	0,216041	440606,06
0,241311	214393,94	0,241306	333030,3	0,241293	486060,61
0,266564	237575,76	0,26656	366212,12	0,266545	534242,42
0,291817	260757,58	0,291813	396818,18	0,291798	569848,48
0,317069	287878,79	0,317065	426363,64	0,317051	600303,03
0,342321	319545,45	0,342317	460757,58	0,342303	637272,73
0,367574	340303,03	0,36757	491060,61	0,367555	667272,73
0,392826	363787,88	0,392822	518181,82	0,392806	698939,39
0,418077	390000	0,418075	543030,3	0,41806	727878,79
0,443329	411515,15	0,443327	573181,82	0,443312	760606,06
0,468584	437121,21	0,468579	591212,12	0,468565	784696,97
0,493835	458030,3	0,493832	616666,67	0,493818	808787,88
0,519088	489393,94	0,519085	643030,3	0,51907	835000
0,544342	503181,82	0,544337	667878,79	0,544324	854848,48
0,569594	535757,58	0,569591	680000	0,569575	873333,33
0,594847	555454,55	0,594843	697575,76	0,594828	896212,12
0,6201	580909,09	0,620095	718484,85	0,620081	922727,27
0,645351	613484,85	0,645349	733484,85	0,645332	943636,36
0,670604	629393,94	0,670601	752424,24	0,670585	972575,76
0,695855	652121,21	0,695852	769696,97	0,695837	994242,42
0,721108	673181,82	0,721105	788939,39	0,721091	1011666,7
0,746361	694848,48	0,746356	803636,36	0,746344	1029848,5
0,771613	726818,18	0,771609	807424,24	0,771596	1050606,1
0,796867	743484,85	0,796863	828787,88	0,796849	1076060,6
0,82212	774545,45	0,822116	845757,58	0,822102	1091515,2
0,847372	793030,3	0,847368	859696,97	0,847353	1120303
0,872625	813181,82	0,872622	867272,73	0,872607	1132878,8
0,897877	840151,52	0,897873	880303,03	0,897858	1155000
0,923128	859848,48	0,923126	892878,79	0,92311	1169242,4
0,948381	891060,61	0,948377	907878,79	0,948362	1196818,2
0,973634	909545,45	0,97363	914090,91	0,973615	1219697
0,998886	936060,61	0,998882	928181,82	0,998868	1235757,6
1,024139	957272,73	1,024134	935000	1,024121	1260151,5
1,049392	974696,97	1,049388	950909,09	1,049374	1276060,6
1,074644	1003484,8	1,074641	964545,45	1,074627	1302424,2
1,099897	1023484,8	1,099893	971363,64	1,099879	1316363,6
1,125151	1053787,9	1,125146	985606,06	1,125132	1340303
1,150402	1081969,7	1,150399	1002575,8	1,150383	1356818,2
1,175655	1101818,2	1,175651	1015303	1,175635	1381363,6
1,200906	1124848,5	1,200904	1037575,8	1,200888	1403787,9

1,226127	1498333,33
1,25138	1524848,48
1,276633	1536363,64
1,301886	1568939,39
1,327138	1589848,48
1,352391	1620303,03
1,377643	1634393,94
1,402896	1658333,33
1,428148	1683333,33
1,4534	1705303,03
1,478652	1734393,94
1,503904	1749848,48
1,529158	1772878,79
1,554411	1801060,61
1,579664	1823484,85
1,604916	1853484,85
1,630169	1871666,67
1,655422	1888181,82
1,680673	1912878,79
1,705926	1935000
1,731178	1961818,18
1,756429	1986666,67
1,781683	2015151,52
1,806936	2028484,85
1,832189	2052272,73
1,857442	2077575,76
1,882694	2108484,85
1,907946	2126363,64
1,933198	2152424,24
1,95845	2182575,76
1,983703	2200606,06
2,008955	2220606,06
2,034207	2247575,76
2,059461	2274090,91
2,084715	2298939,39
2,109967	2318333,33
2,135218	2345000
2,160472	2360000
2,185724	2381363,64
2,210976	2405606,06
2,236229	2428636,36
2,261481	2449545,45
2,286733	2475454,55
2,311985	2499242,42
2,337239	2518636,36
2,362492	2545757,58
2,387744	2552727,27
2,412998	2580454,55
2,438249	2600000
2,463502	2615909,09
2,488754	2641212,12
2,514006	2664090,91

1,226158	1146363,6	1,226155	1050757,6	1,22614	1421060,6
1,251411	1173333,3	1,251407	1077272,7	1,251393	1438636,4
1,276663	1200151,5	1,276659	1081515,2	1,276645	1465151,5
1,301917	1215757,6	1,301913	1102878,8	1,3019	1487878,8
1,327169	1248636,4	1,327165	1120606,1	1,327152	1503636,4
1,352423	1259545,5	1,352419	1136060,6	1,352404	1525000
1,377675	1297727,3	1,377671	1155454,5	1,377658	1550606,1
1,402927	1320909,1	1,402923	1175757,6	1,402908	1563484,8
1,42818	1339393,9	1,428176	1190757,6	1,428161	1587727,3
1,453432	1377727,3	1,453428	1210909,1	1,453413	1613484,8
1,478683	1391212,1	1,47868	1230606,1	1,478665	1636969,7
1,503936	1428939,4	1,503933	1256515,2	1,503918	1651060,6
1,529189	1455151,5	1,529185	1267424,2	1,529171	1678636,4
1,554442	1477272,7	1,554438	1289090,9	1,554423	1702727,3
1,579695	1499848,5	1,579691	1312575,8	1,579677	1720000
1,604948	1528939,4	1,604943	1320909,1	1,604929	1737878,8
1,6302	1552575,8	1,630198	1349393,9	1,630184	1769697
1,655453	1575909,1	1,655448	1362878,8	1,655435	1786060,6
1,680706	1607727,3	1,680702	1379242,4	1,680686	1809545,5
1,705957	1628787,9	1,705955	1402727,3	1,705938	1831060,6
1,731209	1665303	1,731206	1416666,7	1,73119	1850454,5
1,756462	1681818,2	1,756458	1439090,9	1,756443	1873636,4
1,781714	1712121,2	1,78171	1456363,6	1,781697	1895606,1
1,806967	1745909,1	1,806962	1482575,8	1,806948	1910909,1
1,832219	1767727,3	1,832215	1507121,2	1,832202	1945909,1
1,857472	1786363,6	1,857469	1522878,8	1,857455	1968333,3
1,882727	1823333,3	1,882722	1538787,9	1,882707	1989090,9
1,907978	1853484,8	1,907975	1563939,4	1,907959	2008030,3
1,933231	1883181,8	1,933225	1584090,9	1,933211	2039545,5
1,958482	1902727,3	1,95848	1602121,2	1,958464	2060909,1
1,983733	1942424,2	1,983731	1619848,5	1,983715	2081515,2
2,008987	1968636,4	2,008983	1636212,1	2,008969	2103333,3
2,034238	2002727,3	2,034236	1662121,2	2,034222	2123939,4
2,059492	2030151,5	2,059488	1682272,7	2,059475	2161818,2
2,084745	2053333,3	2,08474	1691969,7	2,084727	2174697
2,109998	2089545,5	2,109994	1719393,9	2,10998	2201969,7
2,135251	2122121,2	2,135247	1743484,8	2,135233	2224393,9
2,160503	2153484,8	2,160499	1760909,1	2,160485	2253030,3
2,185756	2180303	2,185752	1776515,2	2,185737	2277121,2
2,21101	2214848,5	2,211005	1795909,1	2,210989	2302878,8
2,236261	2239545,5	2,236257	1809697	2,236241	2326515,2
2,261512	2275606,1	2,26151	1838939,4	2,261493	2349090,9
2,286764	2313030,3	2,286762	1854242,4	2,286747	2371969,7
2,312016	2339545,5	2,312013	1888787,9	2,311999	2403333,3
2,33727	2369848,5	2,337265	1912424,2	2,337253	2424697
2,362523	2410606,1	2,362518	1921969,7	2,362506	2455000
2,387776	2437424,2	2,387772	1937121,2	2,387758	2481969,7
2,413028	2467121,2	2,413025	1962878,8	2,413012	2498787,9
2,438282	2502121,2	2,438277	1983181,8	2,438262	2529242,4
2,463534	2539242,4	2,463529	2009393,9	2,463514	2547272,7
2,488786	2567272,7	2,488782	2025151,5	2,488766	2580454,5
2,494847	1736515,2	2,514034	2058939,4	2,514018	2607878,8

2,539258	2675909,09
2,564511	2700151,52
2,589763	2707575,76
2,615018	2729242,42
2,64027	2742575,76
2,665522	2757121,21
2,690775	2774090,91
2,716027	2773484,85
2,741279	2784848,48
2,766532	2803333,33
2,791784	2822575,76
2,817035	2850757,58
2,842289	2872424,24
2,867542	2887727,27
2,892795	2910151,52
2,918048	2934393,94
2,9433	2963181,82
2,968552	2996515,15
2,993805	3020303,03
3,019056	3046969,7
3,044309	3079848,48
3,069561	3106515,15
3,094813	3143484,85
3,120067	3167424,24
3,145321	3194393,94
3,170572	3224848,48
3,195825	3247727,27
3,221077	3279545,45
3,24633	3309393,94
3,271583	3341212,12
3,296834	3363636,36
3,322087	3393484,85
3,347338	3424545,45
3,372592	3456212,12
3,397845	3481969,7
3,423098	3513787,88
3,44835	3533636,36
3,473604	3566818,18
3,498855	3593636,36
3,524108	3615454,55
3,549359	3644545,45
3,574611	3672727,27
3,589007	2812727,27
3,59027	1975303,03
3,591532	1073787,88
3,592795	206515,152

2,496362	846969,7	2,539287	2069848,5	2,539272	2627121,2
2,497626	76363,636	2,564538	2092424,2	2,564525	2655000
		2,589791	2119090,9	2,589777	2686818,2
		2,615045	2137424,2	2,61503	2704242,4
		2,640297	2169848,5	2,640283	2736818,2
		2,665549	2187272,7	2,665536	2753181,8
		2,690803	2209545,5	2,690788	2781818,2
		2,716055	2233333,3	2,71604	2813181,8
		2,741307	2246666,7	2,741292	2841969,7
		2,76656	2287424,2	2,766544	2865606,1
		2,791812	2298030,3	2,791796	2883787,9
		2,817064	2322272,7	2,817049	2911969,7
		2,842316	2339090,9	2,842304	2938484,8
		2,867568	2360757,6	2,867555	2975606,1
		2,892822	2388939,4	2,892808	2999393,9
		2,918075	2413484,8	2,918062	3026212,1
		2,943328	2431212,1	2,943313	3054697
		2,968581	2458181,8	2,968566	3076666,7
		2,993832	2483030,3	2,993817	3097878,8
		3,019085	2496666,7	3,019068	3133333,3
		3,044338	2518484,8	3,044322	3164242,4
		3,069588	2548030,3	3,069574	3184090,9
		3,094842	2574242,4	3,094828	3214848,5
		3,120094	2596515,2	3,120081	3239545,5
		3,145347	2620909,1	3,145333	3268939,4
		3,170601	2640454,5	3,170586	3298333,3
		3,195852	2666818,2	3,195839	3330303
		3,221105	2684393,9	3,221091	3352272,7
		3,246358	2714090,9	3,246343	3380000
		3,27161	2730303	3,271595	3411212,1
		3,296863	2751969,7	3,296847	3439697
		3,322115	2777878,8	3,3221	3468030,3
		3,347367	2806515,2	3,347353	3504242,4
		3,372619	2821060,6	3,372606	3530000
		3,397872	2852424,2	3,397858	3553484,8
		3,423125	2877272,7	3,423111	3585000
		3,448378	2902272,7	3,448364	3608787,9
		3,473631	2929848,5	3,473618	3639393,9
		3,498883	2953333,3	3,498868	3670606,1
		3,524135	2981818,2	3,524119	3710909,1
		3,549388	3003939,4	3,549373	3730757,6
		3,57464	3017878,8	3,574625	3768939,4
		3,599892	3043484,8	3,599878	3797272,7
		3,625144	3072121,2	3,625132	3819090,9
		3,650396	3096969,7	3,650383	3848787,9
		3,675651	3126363,6	3,675636	3882878,8
		3,700903	3140303	3,700888	3916515,2
		3,726156	3174697	3,726141	3947272,7
		3,751409	3191212,1	3,751395	3986515,2
		3,77666	3220000	3,771342	3076818,2
		3,801914	3245757,6	3,772604	2194242,4
		3,827165	3270909,1	3,773615	1432575,8

3,852418	3293333,3	3,774877	504242,42
3,87767	3323484,8		
3,902922	3350909,1		
3,928175	3377727,3		
3,953428	3401666,7		
3,978681	3430454,5		
4,003935	3459848,5		
4,029187	3480757,6		
4,054438	3514848,5		
4,079692	3538333,3		
4,104942	3563484,8		
4,130196	3592727,3		
4,155448	3622575,8		
4,180699	3652727,3		
4,205953	3679545,5		
4,231207	3699242,4		
4,256458	3729545,5		
4,281711	3760606,1		
4,306964	3787575,8		
4,332216	3821060,6		
4,357468	3840000		
4,382722	3876212,1		
4,407973	3905303		
4,433225	3935454,5		
4,458478	3958030,3		
4,483731	3989545,5		
4,508984	4014697		
4,534237	4055151,5		
4,55949	4076363,6		
4,584742	4115757,6		
4,609993	4138484,8		
4,635246	4170454,5		
4,660498	4205454,5		
4,68575	4241818,2		
4,711003	4286666,7		
4,736256	4311969,7		
4,76151	4342575,8		
4,786763	4373030,3		
4,79484	3455000		
4,796104	2522727,3		
4,797115	1713181,8		
4,798124	913030,3		

Shore 65 @80degree		Shore 75 @80degree		shore 85 @80degree	
strain	stress	strain	stress	strain	stress
mm/mm	N/m²	mm/mm	N/m²	mm/mm	N/m²
0	-44696,97	0	-55909,09	0	-62878,79
0,011917	119393,94	0,011903	99848,485	0,01193	102727,3
0,039115	8030,303	0,039104	-7272,727	0,03913	18484,85
0,064523	61363,636	0,064517	76818,182	0,064538	98636,36
0,089781	89848,485	0,089775	111666,67	0,089796	158030,3
0,115033	109848,48	0,115027	156666,67	0,115047	216515,2
0,140286	142575,76	0,14028	203333,33	0,140301	272424,2
0,165538	167424,24	0,165532	242727,27	0,165552	323787,9
0,190789	184545,45	0,190784	284242,42	0,190804	379697
0,216041	208333,33	0,216036	326212,12	0,216058	431363,6
0,241295	234696,97	0,241288	360454,55	0,241311	477575,8
0,266548	256666,67	0,266541	395303,03	0,266564	523484,8
0,291802	271212,12	0,291795	418333,33	0,291816	554545,5
0,317054	295454,55	0,317048	452272,73	0,317068	598636,4
0,342305	319090,91	0,3423	472878,79	0,342322	628333,3
0,367559	352272,73	0,367553	511212,12	0,367573	666363,6
0,392812	371212,12	0,392805	537272,73	0,392825	691818,2
0,418063	394393,94	0,418057	553484,85	0,418078	718636,4
0,443316	410000	0,443309	568636,36	0,44333	754090,9
0,468567	429545,45	0,46856	607878,79	0,468582	783333,3
0,493821	465303,03	0,493813	621515,15	0,493836	810757,6
0,519074	467424,24	0,519067	645000	0,519088	817272,7
0,544326	492878,79	0,54432	655909,09	0,544341	851969,7
0,569579	502878,79	0,569574	680000	0,569594	872575,8
0,594832	523939,39	0,594826	700303,03	0,594847	888787,9
0,620084	541969,7	0,620077	715454,55	0,620098	916060,6
0,645336	559242,42	0,645331	736212,12	0,64535	937121,2
0,670589	578484,85	0,670584	749242,42	0,670604	962424,2
0,695841	593787,88	0,695834	762121,21	0,695855	981212,1
0,721093	619393,94	0,721087	791666,67	0,721108	1013788
0,746345	634545,45	0,746339	805454,55	0,74636	1031061
0,771597	645454,55	0,771592	820606,06	0,771613	1052424
0,796852	667272,73	0,796844	836969,7	0,796866	1065000
0,822104	679545,45	0,822098	857727,27	0,822119	1082121
0,847357	698030,3	0,84735	882272,73	0,847372	1104848
0,87261	718484,85	0,872603	893484,85	0,872624	1131212
0,897862	739090,91	0,897856	919090,91	0,897876	1153333
0,923114	751969,7	0,923108	930606,06	0,923129	1171364
0,948367	772727,27	0,94836	954848,48	0,94838	1196970
0,973618	792121,21	0,973612	967878,79	0,973633	1219697
0,99887	808030,3	0,998864	989848,48	0,998886	1225606
1,024124	820909,09	1,024117	1002878,8	1,024138	1253182
1,049377	849545,45	1,04937	1028939,4	1,049392	1278788
1,074629	857575,76	1,074623	1038484,8	1,074644	1294394
1,099882	879848,48	1,099875	1061363,6	1,099897	1313485
1,125134	903181,82	1,125128	1075303	1,125149	1331364
1,150387	918333,33	1,150381	1097727,3	1,150401	1356061
1,175639	934545,45	1,175633	1106212,1	1,175654	1375606
1,200892	941515,15	1,200885	1136969,7	1,200906	1399091

1,226144	969090,91	1,226139	1155757,6	1,226158	1417727
1,251395	987727,27	1,25139	1169393,9	1,251411	1438030
1,276648	1002121,2	1,276642	1187424,2	1,276663	1464242
1,301901	1023181,8	1,301895	1206363,6	1,301916	1486515
1,327154	1038939,4	1,327148	1228939,4	1,32717	1503182
1,352408	1056060,6	1,352401	1238333,3	1,352423	1515303
1,377659	1086818,2	1,377653	1266363,6	1,377675	1548636
1,402912	1099090,9	1,402906	1274545,5	1,402926	1564091
1,428165	1114545,5	1,428159	1295757,6	1,428179	1576515
1,453417	1131818,2	1,45341	1310303	1,453431	1604394
1,478669	1156212,1	1,478665	1326666,7	1,478684	1623939
1,503922	1176515,2	1,503915	1343484,8	1,503936	1651212
1,529173	1200303	1,529166	1360757,6	1,529189	1662273
1,554426	1212272,7	1,55442	1387121,2	1,554443	1682424
1,579681	1232272,7	1,579674	1407272,7	1,579694	1699697
1,604932	1255151,5	1,604926	1424090,9	1,604947	1718333
1,630185	1271515,2	1,63018	1443333,3	1,630201	1740303
1,655438	1297121,2	1,655432	1471212,1	1,655452	1755152
1,68069	1306666,7	1,680684	1491818,2	1,680705	1779848
1,705943	1331515,2	1,705936	1502575,8	1,705957	1795152
1,731194	1344545,5	1,731188	1521212,1	1,731209	1816212
1,756447	1376212,1	1,756441	1541969,7	1,756462	1833485
1,781699	1400000	1,781693	1552575,8	1,781713	1856515
1,80695	1410909,1	1,806946	1575909,1	1,806966	1868030
1,832204	1436666,7	1,832198	1591060,6	1,832219	1886970
1,857458	1456363,6	1,857451	1618939,4	1,857472	1901667
1,882709	1475454,5	1,882704	1640000	1,882726	1916818
1,907964	1505454,5	1,907956	1655454,5	1,907978	1933333
1,933215	1523181,8	1,93321	1675454,5	1,933229	1941364
1,958468	1542878,8	1,958462	1696060,6	1,958482	1960606
1,98372	1561818,2	1,983715	1720909,1	1,983734	1976515
2,008972	1587878,8	2,008965	1737878,8	2,008986	1991818
2,034225	1600606,1	2,034218	1752424,2	2,034239	2018030
2,059476	1622424,2	2,05947	1776969,7	2,059491	2028333
2,084729	1640151,5	2,084722	1793484,8	2,084745	2052879
2,109983	1672727,3	2,109976	1810909,1	2,109998	2073030
2,135236	1692121,2	2,135231	1836515,2	2,13525	2102727
2,160488	1712424,2	2,160482	1845454,5	2,160503	2112727
2,18574	1741818,2	2,185735	1871818,2	2,185756	2141061
2,210994	1756515,2	2,210987	1894242,4	2,211007	2159091
2,236245	1782727,3	2,236239	1920606,1	2,236259	2180606
2,261497	1809242,4	2,261492	1929545,5	2,261512	2207273
2,286751	1836212,1	2,286744	1954090,9	2,286765	2219091
2,312002	1855757,6	2,311996	1980303	2,312017	2251818
2,337255	1878181,8	2,337248	2000000	2,33727	2269394
2,362507	1902878,8	2,362501	2016818,2	2,362522	2300000
2,387761	1923484,8	2,387754	2043181,8	2,387776	2316818
2,413015	1960000	2,413007	2062878,8	2,413028	2348030
2,438265	1971212,1	2,438259	2077272,7	2,438281	2368333
2,463518	1998333,3	2,463513	2100000	2,463534	2390909
2,488771	2029697	2,488765	2123333,3	2,488785	2409545
2,514022	2046060,6	2,514017	2151666,7	2,514037	2441212

2,539275	2074393,9	2,539268	2174393,9	2,539289	2455758
2,564529	2093787,9	2,564522	2186212,1	2,564542	2487727
2,589779	2116363,6	2,589772	2203636,4	2,589795	2511667
2,615033	2152727,3	2,615026	2238484,8	2,615048	2531970
2,640285	2167424,2	2,640279	2250000	2,640301	2561212
2,665539	2202121,2	2,665532	2272272,7	2,665553	2579848
2,690791	2228333,3	2,690786	2293939,4	2,690806	2598485
2,716043	2243181,8	2,716038	2318787,9	2,716058	2627273
2,741297	2282727,3	2,741289	2337575,8	2,741311	2646515
2,766549	2300151,5	2,766543	2352121,2	2,766562	2668788
2,7918	2323484,8	2,791794	2380606,1	2,791815	2693939
2,817052	2356060,6	2,817046	2407424,2	2,817067	2718182
2,842305	2386515,2	2,842299	2426515,2	2,84232	2744848
2,867558	2403787,9	2,867551	2450303	2,867572	2762273
2,892811	2438787,9	2,892805	2473787,9	2,892826	2786364
2,918063	2460454,5	2,918057	2489242,4	2,918078	2816667
2,943316	2491666,7	2,94331	2520151,5	2,943332	2839091
2,968569	2514848,5	2,968562	2541818,2	2,968584	2859394
2,993822	2539848,5	2,993815	2568333,3	2,993835	2889091
3,019074	2565454,5	3,019068	2587272,7	3,019088	2914394
3,044325	2596363,6	3,04432	2617272,7	3,04434	2932727
3,069578	2633181,8	3,069572	2631060,6	3,069592	2961212
3,094829	2660909,1	3,094825	2657727,3	3,094846	2985455
3,120084	2684545,5	3,120076	2685000	3,120097	3010152
3,145336	2711515,2	3,145329	2704242,4	3,14535	3041970
3,170589	2745303	3,170582	2732272,7	3,170605	3056515
3,195842	2764090,9	3,195836	2744545,5	3,195855	3087879
3,205436	1894090,9	3,221088	2775151,5	3,221109	3113788
3,206698	1136060,6	3,246341	2795454,5	3,246361	3147424
3,207962	336212,12	3,271592	2819242,4	3,271613	3170152
		3,296845	2844848,5	3,296866	3188939
		3,322097	2857272,7	3,322117	3221364
		3,34735	2895606,1	3,347371	3244242
		3,372602	2913181,8	3,372623	3267879
		3,397854	2938787,9	3,397875	3298485
		3,423107	2960000	3,423129	3325606
		3,434219	2084697	3,448381	3343939
		3,435482	1318939,4	3,473634	3376818
		3,436745	509848,48	3,498887	3396212
				3,524138	3424697
				3,549391	3451515
				3,574643	3479394
				3,599896	3505909
				3,625148	3530000
				3,6504	3557424
				3,675654	3585758
				3,700907	3611515
				3,72616	3636364
				3,751412	3672121
				3,776663	3695303
				3,801917	3720303
				3,827168	3746970

3,852421	3774394
3,877674	3802273
3,902926	3823182
3,928179	3855909
3,953431	3880000
3,978684	3904394
4,003938	3939697
4,02919	3961970
4,054443	3991515
4,079694	4015606
4,104945	4049242
4,130199	4073788
4,155452	4098636
4,180704	4126667
4,205957	4153333
4,23121	4182273
4,256462	4210909
4,281715	4234394
4,306967	4258939
4,332219	4290758
4,357471	4320152
4,382724	4339242
4,407976	4373485
4,433229	4396515
4,458482	4422879
4,483735	4447273
4,508988	4481970
4,53424	4511667
4,541817	3734091
4,543078	2821667
4,544089	2011515
4,545098	1196818
4,546108	424697

Appendix 4 IK Standard

HI-SEAL TABULATION

PIG NS"	BODY TUBE	FLANGE DIA	No. of HOLES	BOLT SIZE	P.C.D.	BYPASS " BSP	DISC THICKNESS SEAL. STD	DISC THICKNESS SEAL T.W.	DISC THICKNESS GUIDE	DISC THICKNESS SPACER	DISC I/D GUIDE / SPACER	DISC I/D SEAL	FASTENER THICKNESSES NUT THK	FASTENER THICKNESSES WASHER THK	FASTENER THICKNESSES BOLT HEAD THK	No. of Spring Mounted BRUSHES	Magnet Box No.	No. of MAGNET PACKS
3	21.1	45	4	M5	34		5	-	10	10			5	1	4	-		-
4	34	70	6	M5	52	1/8"	5	-	10	10	35	35	5	1	4	-		
6	48	100	6	M6	80	1/8"	8	-	15	15	50	50	8	1.6	5	-	0	2
8	60	135	8	M8	100	1/4"	10	-	20	20	62	62	9	2	6	-	1	3
9	60	150	8	M8	100	1/4"	10	-	20	20	62	62	9	2	6	-	1	3
10	89	170	8	M10	130	1/4"	15	-	25	25	92	92	11	2.5	8	-	1	4
12	114	205	8	M10	170	1/4"	15	-	25	25	118	119	11	2.5	8		1	5
14	114	240	8	M12	190	1/4"	15	12	25	25	118	119	14	3	10	6	1	5
16	141	270	8	M12	210	1/2"	15	13	25	25	145	146	14	3	10	6	2	5
18	168	305	12	M12	235	1/2"	20	13	30	30	173	174	14	3	10	6	2	6
20	219	340	12	M12	280	1/2"	20	13	30	30	225	226	14	3	10	6	2	6
22	273	400	12	M16	346	1"	20	13	30	30	276	277	16	3.5	12	6	2	8
24	273	400	12	M16	346	1"	20	18	30	30	276	277	16	3.5	12	8	2	8
26	356	470	12	M16	410	1"	25	18	35	35	360	362	16	3.5	12	8	2	8
28	356	515	12	M16	460	1"	25	18	35	35	360	362	16	3.5	12	10	2	8
30	406	570	12	M16	520	1"	25	18	40	40	410	412	16	3.5	12	10	3	8
32	457	600	12	M16	550	1"	25	18	40	40	460	462	16	3.5	12	10	3	8
34	457	630	12	M20	570	1"	30	-	40	40	460	462	22	4	17	12	3	8
36	508	660	12	M20	600	1½"	30	22	45	45	515	518	22	4	17	12	3	8
38	508	660	12	M20	600	1½"	30	22	45	45	515	518	22	4	17	12	3	8
40	610	815	16	M20	715	1½"	30	22	45	45	615	618	22	4	17	16	3	12
42	610	840	16	M20	730	1½"	30	-	45	45	615	618	22	4	17	16	3	12
44	610	880	16	M20	750	1½"	30	-	45	45	615	618	22	4	17	16	3	12
46/48	660	920	16	M20	800	2"	30	-	50	50	667	669	22	4	17	16	3	12
~~46/48~~	~~762~~	~~960~~	~~16~~	~~M20~~	~~860~~	~~2"~~	~~30~~	-	~~45~~	~~45~~	~~767~~	~~770~~	~~22~~	4	~~17~~	~~18~~	~~3~~	~~12~~
56	762	1020	24	M20	900	2"	45	-	60	60	767	770	22	4	17	20	3	12

SEAL INTERFERENCE		GUIDE CLEARANCE	
4"-8"	I/D + 6-8	4"-8"	I/D -2
9"-14"	I/D + 16-20	9"-14"	I/D -4
16"-24"	I/D + 20-24	16"-34"	I/D -6
26"-34"	I/D + 24-30	36" +	I/D -12
34"-48"	I/D + 30-35		
50"-62"	I/D + 35-40		

BRUSH INTERFERENCE (ON DIA.) CIRCULAR		HS SPRING		CUP SPRING	
6"-8"	I/D +1-2	6"-10"	10	6"-10"	20
10"-14"	I/D +3-6	12"-16"	12	12"-16"	25
16"-36"	I/D +6-10	18"-24"	15	18"-24"	30
36" +	I/D +10-15	26"-48"	17-28	26"-48"	35-45

SPINDLE BODY PIGS PIG ns"	Spindle Ø	CTR SPACER THK.	Disc ID
3"			
4"	M16	46	17mm
6"	M20	60	21mm
8"	M20	2 x 42	21mm
9"	M20	2 x 60	21mm
10"	M30	2 x 60	32mm
12"	M30	3 x 56	32mm

P:\General\General Eng\HIGH SEAL DATA.xlsx MASTER TABLE Rev'G 08-12-14 08/12/2014 1/1

Appendix 5 Deflection of Shore grade calculation results

Plate characteristics for simple bending for shore grade 65 at 20 ºC

Youngs Modulus $E := 6.157MPa$

Possion ratio $v := 0.47$

Radius of Plate $R := 0.10487m$

Thickness of Plate $H := 0.01m$

Mid Plate Thickness $h := \frac{H}{2}$

Uniform Pressure $P := 0.02MPa$

Radius at the Edge $r := 0mm$

1 - Maximum Deflection at center for r = 0

A - CALCULATIONS

$$D := \frac{2.E \cdot h^3}{3(1 - v^2)}$$

$$D = 0.659\,J$$

The general deflection equation for simple support is given by:

$$W_{max} := \frac{P \cdot R^4}{64.D}\left(\frac{5 + v}{1 + v}\right)$$

$$W_{max} = 0.214\,m$$

2 - Bending Moment along the r-axis at center for r = 0

B - CALCULATIONS

$$M_{rr} := \frac{P}{16}(3 + v)(R^2 - r^2)$$

$$M_{rr} = 47.703\,N$$

3 - Bending Moment along the Θ -axis at center for r = 0

C - CALCULATIONS

$$M_{\Theta\Theta} := \frac{P}{16}\left[(1 + v)R^2 - (1 + 3v)r^2\right]$$

$$M_{\Theta\Theta} = 20.208\,N$$

4 - Shear stress at r=R

D - CALCULATIONS

The general equation for shear force is given by $S_{rr} := \frac{P \cdot R}{2}$

$$S_{rr} = 1.049 \times 10^3 \frac{kg}{s^2}$$

Plate characteristics for simple bending for shore grade 65 at 40 ºC

Youngs Modulus $E := 4.596 MPa$

Possion ratio $v := 0.47$

Radius of Plate $R := 0.10487m$

Thickness of Plate $H := 0.01m$

Mid Plate thickness $h := \frac{H}{2}$

Uniform Pressure $P := 0.02 MPa$

Radius at the Edge $r := 0mm$

1 - Maximum Deflection at center for r = 0

A - CALCULATIONS

$$D := \frac{2.E \cdot h^3}{3(1 - v^2)}$$

$$D = 0.492 J$$

The general deflection equation for simple support is given by:

$$W_{max} := \frac{P \cdot R^4}{64.D}\left(\frac{5 + v}{1 + v}\right)$$

$$W_{max} = 0.286 m$$

2 - Bending Moment along the r-axis at center for r = 0

B - CALCULATIONS

$$M_{rr} := \frac{P}{16}(3 + v)\left(R^2 - r^2\right)$$

$$M_{rr} = 47.703 N$$

3 - Bending Moment along the Θ -axis at center for r = 0

C - CALCULATIONS

$$M_{\Theta\Theta} := \frac{P}{16}\left[(1 + v)R^2 - (1 + 3v)r^2\right]$$

$$M_{\Theta\Theta} = 20.208 N$$

4 - Shear stress at r=R

D - CALCULATIONS

The general equation for shear force is given by

$$S_{rr} := \frac{P \cdot R}{2}$$

$$S_{rr} = 1.049 \times 10^3 \frac{kg}{s^2}$$

Plate characteristics for simple bending for shore grade 65 at 60 ºC

Youngs Modulus $E := 3.5985MPa$

Possion ratio $v := 0.47$

Radius of Plate $R := 0.10487m$

Thickness of Plate $H := 0.01m$

Mid Plate thickness $h := \frac{H}{2}$

Uniform Pressure $P := 0.02MPa$

Radius at the Edge $r := 0mm$

1 - Maximum Deflection at center for r = 0

A - CALCULATIONS

$$D := \frac{2.E \cdot h^3}{3(1 - v^2)}$$

$$D = 0.385\,J$$

The general deflection equation for simple support is given by:

$$W_{max} := \frac{P \cdot R^4}{64.D}\left(\frac{5 + v}{1 + v}\right)$$

$$W_{max} = 0.365\,m$$

2 - Bending Moment along the r-axis at center for r = 0

B - CALCULATIONS

$$M_{rr} := \frac{P}{16}(3 + v)(R^2 - r^2)$$

$$M_{rr} = 47.703\,N$$

3 - Bending Moment along the Θ -axis at center for r = 0

C - CALCULATIONS

$$M_{\Theta\Theta} := \frac{P}{16}\left[(1 + v)R^2 - (1 + 3v)r^2\right]$$

$$M_{\Theta\Theta} = 20.208\,N$$

4 - Shear stress at r=R

D - CALCULATIONS

The general equation for shear force is given by

$$S_{rr} := \frac{P \cdot R}{2}$$

$$S_{rr} = 1.049 \times 10^3 \frac{kg}{s^2}$$

Plate characteristics for simple bending for shore grade 65 at 70 ºC

Youngs Modulus $E := 2.5MPa$

Possion ratio $v := 0.47$

Radius of Plate $R := 0.10487m$

Thickness of Plate $H := 0.01m$

Mid Plate thickness $h := \frac{H}{2}$

Uniform Pressure $P := 0.02MPa$

Radius at the Edge $r := 0mm$

1 - Maximum Deflection at center for r = 0

A - CALCULATIONS

$$D := \frac{2.E \cdot h^3}{3\left(1 - v^2\right)}$$

$$D = 0.267\,J$$

The general deflection equation for simple support is given by:

$$W_{max} := \frac{P \cdot R^4}{64.D}\left(\frac{5 + v}{1 + v}\right)$$

$$W_{max} = 0.526\,m$$

2 - Bending Moment along the r-axis at center for r = 0

B - CALCULATIONS

$$M_{rr} := \frac{P}{16}(3 + v)\left(R^2 - r^2\right)$$

$$M_{rr} = 47.703\,N$$

3 - Bending Moment along the Θ -axis at center for r = 0

C - CALCULATIONS

$$M_{\Theta\Theta} := \frac{P}{16}\left[(1 + v)R^2 - (1 + 3v)r^2\right]$$

$$M_{\Theta\Theta} = 20.208\,N$$

4 - Shear stress at r=R

D - CALCULATIONS

The general equation for shear force is given by

$$S_{rr} := \frac{P \cdot R}{2}$$

$$S_{rr} = 1.049 \times 10^3 \frac{kg}{s^2}$$

Plate characteristics for simple bending for shore grade 65 at 80 ºC

Youngs Modulus $E := 3.7247MPa$

Possion ratio $v := 0.47$

Radius of Plate $R := 0.10487m$

Thickness of Plate $H := 0.01m$

Mid Plate thickness $h := \frac{H}{2}$

Uniform Pressure $P := 0.02MPa$

Radius at the Edge $r := 0mm$

1 - Maximum Deflection at center for r = 0

A - CALCULATIONS

$$D := \frac{2.E \cdot h^3}{3(1 - v^2)}$$

$$D = 0.398 J$$

The general deflection equation for simple support is given by:

$$W_{max} := \frac{P \cdot R^4}{64.D}\left(\frac{5 + v}{1 + v}\right)$$

$$W_{max} = 0.353 m$$

2 - Bending Moment along the r-axis at center for r = 0

B - CALCULATIONS

$$M_{rr} := \frac{P}{16}(3 + v)(R^2 - r^2)$$

$$M_{rr} = 47.703 N$$

3 - Bending Moment along the Θ -axis at center for r = 0

C - CALCULATIONS

$$M_{\Theta\Theta} := \frac{P}{16}\left[(1 + v)R^2 - (1 + 3v)r^2\right]$$

$$M_{\Theta\Theta} = 20.208 N$$

4 - Shear stress at r=R

D - CALCULATIONS

The general equation for shear force is given by

$$S_{rr} := \frac{P \cdot R}{2}$$

$$S_{rr} = 1.049 \times 10^3 \frac{kg}{s^2}$$

Plate characteristics for simple bending for shore grade 75 at 20 ºC

Youngs Modulus $E := 6.5014MPa$

Possion ratio $v := 0.47$

Radius of Plate $R := 0.10487m$

Thickness of Plate $H := 0.01m$

Mid Plate thickness $h := \frac{H}{2}$

Uniform Pressure $P := 0.02MPa$

Radius at the Edge $r := 0mm$

1 - Maximum Deflection at center for r = 0

A - CALCULATIONS

$$D := \frac{2.E \cdot h^3}{3\left(1 - v^2\right)}$$

$$D = 0.695\,J$$

The general deflection equation for simple support is given by:

$$W_{max} := \frac{P \cdot R^4}{64.D}\left(\frac{5 + v}{1 + v}\right)$$

$$W_{max} = 0.202\,m$$

2 - Bending Moment along the r-axis at center for r = 0

B - CALCULATIONS

$$M_{rr} := \frac{P}{16}(3 + v)\left(R^2 - r^2\right)$$

$$M_{rr} = 47.703\,N$$

3 - Bending Moment along the Θ -axis at center for r = 0

C - CALCULATIONS

$$M_{\Theta\Theta} := \frac{P}{16}\left[(1 + v)R^2 - (1 + 3v)r^2\right]$$

$$M_{\Theta\Theta} = 20.208\,N$$

4 - Shear stress at r=R

D - CALCULATIONS

The general equation for shear force is given by

$$S_{rr} := \frac{P \cdot R}{2}$$

$$S_{rr} = 1.049 \times 10^3 \frac{kg}{s^2}$$

Plate characteristics for simple bending for shore grade 75 at 40 ºC

Youngs Modulus	$E := 5.3283MPa$
Possion ratio	$v := 0.47$
Radius of Plate	$R := 0.10487m$
Thickness of Plate	$H := 0.01m$
Mid Plate thickness	$h := \frac{H}{2}$
Uniform Pressure	$P := 0.02MPa$
Radius at the Edge	$r := 0mm$

1 - Maximum Deflection at center for r = 0

A - CALCULATIONS

$$D := \frac{2.E \cdot h^3}{3\left(1 - v^2\right)}$$

$$D = 0.57\,J$$

The general deflection equation for simple support is given by:

$$W_{max} := \frac{P \cdot R^4}{64.D}\left(\frac{5 + v}{1 + v}\right)$$

$$W_{max} = 0.247\,m$$

2 - Bending Moment along the r-axis at center for r = 0

B - CALCULATIONS

$$M_{rr} := \frac{P}{16}(3 + v)\left(R^2 - r^2\right)$$

$$M_{rr} = 47.703\,N$$

3 - Bending Moment along the Θ -axis at center for r = 0

C - CALCULATIONS

$$M_{\Theta\Theta} := \frac{P}{16}\left[(1 + v)R^2 - (1 + 3v)r^2\right]$$

$$M_{\Theta\Theta} = 20.208\,N$$

4 - Shear stress at r=R

D - CALCULATIONS

The general equation for shear force is given by

$$S_{rr} := \frac{P \cdot R}{2}$$

$$S_{rr} = 1.049 \times 10^3 \frac{kg}{s^2}$$

Plate characteristics for simple bending for shore grade 75 at 60 ºC

Youngs Modulus $E := 4.2045MPa$

Possion ratio $v := 0.47$

Radius of Plate $R := 0.10487m$

Thickness of Plate $H := 0.01m$

Mid Plate thickness $h := \frac{H}{2}$

Uniform Pressure $P := 0.02MPa$

Radius at the Edge $r := 0mm$

1 - Maximum Deflection at center for r = 0

A - CALCULATIONS

$$D := \frac{2.E \cdot h^3}{3(1 - v^2)}$$

$$D = 0.45 J$$

The general deflection equation for simple support is given by:

$$W_{max} := \frac{P \cdot R^4}{64.D}\left(\frac{5 + v}{1 + v}\right)$$

$$W_{max} = 0.313 m$$

2 - Bending Moment along the r-axis at center for r = 0

B - CALCULATIONS

$$M_{rr} := \frac{P}{16}(3 + v)\left(R^2 - r^2\right)$$

$$M_{rr} = 47.703 N$$

3 - Bending Moment along the Θ -axis at center for r = 0

C - CALCULATIONS

$$M_{\Theta\Theta} := \frac{P}{16}\left[(1 + v)R^2 - (1 + 3v)r^2\right]$$

$$M_{\Theta\Theta} = 20.208 N$$

4 - Shear stress at r=R

D - CALCULATIONS

The general equation for shear force is given by

$$S_{rr} := \frac{P \cdot R}{2}$$

$$S_{rr} = 1.049 \times 10^3 \frac{kg}{s^2}$$

Plate characteristics for simple bending for shore grade 75 at 70 ºC

Youngs Modulus $E := 4.621 MPa$

Possion ratio $v := 0.47$

Radius of Plate $R := 0.10487m$

Thickness of Plate $H := 0.01m$

Mid Plate thickness $h := \frac{H}{2}$

Uniform Pressure $P := 0.02MPa$

Radius at the Edge $r := 0mm$

1 - Maximum Deflection at center for r = 0

A - CALCULATIONS

$$D := \frac{2.E \cdot h^3}{3(1 - v^2)}$$

$$D = 0.494 J$$

The general deflection equation for simple support is given by:

$$W_{max} := \frac{P \cdot R^4}{64.D}\left(\frac{5 + v}{1 + v}\right)$$

$$W_{max} = 0.285 m$$

2 - Bending Moment along the r-axis at center for r = 0

B - CALCULATIONS

$$M_{rr} := \frac{P}{16}(3 + v)(R^2 - r^2)$$

$$M_{rr} = 47.703 N$$

3 - Bending Moment along the Θ -axis at center for r = 0

C - CALCULATIONS

$$M_{\Theta\Theta} := \frac{P}{16}\left[(1 + v)R^2 - (1 + 3v)r^2\right]$$

$$M_{\Theta\Theta} = 20.208 N$$

4 - Shear stress at r=R

D - CALCULATIONS

The general equation for shear force is given by

$$S_{rr} := \frac{P \cdot R}{2}$$

$$S_{rr} = 1.049 \times 10^3 \frac{kg}{s^2}$$

Plate characteristics for simple bending for shore grade 75 at 80 ºC

Youngs Modulus $E := 4.6591MPa$

Possion ratio $v := 0.47$

Radius of Plate $R := 0.10487m$

Thickness of Plate $H := 0.01m$

Mid Plate thickness $h := \frac{H}{2}$

Uniform Pressure $P := 0.02MPa$

Radius at the Edge $r := 0mm$

1 - Maximum Deflection at center for r = 0

A - CALCULATIONS

$$D := \frac{2.E \cdot h^3}{3\left(1 - v^2\right)}$$

$$D = 0.498\,J$$

The general deflection equation for simple support is given by:

$$W_{max} := \frac{P \cdot R^4}{64.D}\left(\frac{5 + v}{1 + v}\right)$$

$$W_{max} = 0.282\,m$$

2 - Bending Moment along the r-axis at center for r = 0

B - CALCULATIONS

$$M_{rr} := \frac{P}{16}(3 + v)\left(R^2 - r^2\right)$$

$$M_{rr} = 47.703\,N$$

3 - Bending Moment along the Θ -axis at center for r = 0

C - CALCULATIONS

$$M_{\Theta\Theta} := \frac{P}{16}\left[(1 + v)R^2 - (1 + 3v)r^2\right]$$

$$M_{\Theta\Theta} = 20.208\,N$$

4 - Shear stress at r=R

D - CALCULATIONS

The general equation for shear force is given by

$$S_{rr} := \frac{P \cdot R}{2}$$

$$S_{rr} = 1.049 \times 10^3 \frac{kg}{s^2}$$

Plate characteristics for simple bending for shore grade 85 at 20 ºC

Youngs Modulus $E := 7.2096MPa$

Possion ratio $v := 0.47$

Radius of Plate $R := 0.10487m$

Thickness of Plate $H := 0.01m$

Mid Plate thickness $h := \frac{H}{2}$

Uniform Pressure $P := 0.02MPa$

Radius at the Edge $r := 0mm$

1 - Maximum Deflection at center for r = 0

A - CALCULATIONS

$$D := \frac{2.E \cdot h^3}{3\left(1 - v^2\right)}$$

$$D = 0.771\,J$$

The general deflection equation for simple support is given by:

$$W_{max} := \frac{P \cdot R^4}{64.D}\left(\frac{5 + v}{1 + v}\right)$$

$$W_{max} = 0.182\,m$$

2 - Bending Moment along the r-axis at center for r = 0

B - CALCULATIONS

$$M_{rr} := \frac{P}{16}(3 + v)\left(R^2 - r^2\right)$$

$$M_{rr} = 47.703\,N$$

3 - Bending Moment along the Θ -axis at center for r = 0

C - CALCULATIONS

$$M_{\Theta\Theta} := \frac{P}{16}\left[(1 + v)R^2 - (1 + 3v)r^2\right]$$

$$M_{\Theta\Theta} = 20.208\,N$$

4 - Shear stress at r=R

D - CALCULATIONS

The general equation for shear force is given by

$$S_{rr} := \frac{P \cdot R}{2}$$

$$S_{rr} = 1.049 \times 10^3 \frac{kg}{s^2}$$

Plate characteristics for simple bending for shore grade 85 at 40 ºC

Youngs Modulus $E := 6.7929MPa$

Possion ratio $v := 0.47$

Radius of Plate $R := 0.10487m$

Thickness of Plate $H := 0.01m$

Mid Plate thickness $h := \frac{H}{2}$

Uniform Pressure $P := 0.02MPa$

Radius at the Edge $r := 0mm$

1 - Maximum Deflection at center for r = 0

A - CALCULATIONS

$$D := \frac{2.E \cdot h^3}{3(1 - v^2)}$$

$$D = 0.727 J$$

The general deflection equation for simple support is given by:

$$W_{max} := \frac{P \cdot R^4}{64.D}\left(\frac{5 + v}{1 + v}\right)$$

$$W_{max} = 0.194 m$$

2 - Bending Moment along the r-axis at center for r = 0

B - CALCULATIONS

$$M_{rr} := \frac{P}{16}(3 + v)(R^2 - r^2)$$

$$M_{rr} = 47.703 N$$

3 - Bending Moment along the Θ -axis at center for r = 0

C - CALCULATIONS

$$M_{\Theta\Theta} := \frac{P}{16}\left[(1 + v)R^2 - (1 + 3v)r^2\right]$$

$$M_{\Theta\Theta} = 20.208 N$$

4 - Shear stress at r=R

D - CALCULATIONS

The general equation for shear force is given by

$$S_{rr} := \frac{P \cdot R}{2}$$

$$S_{rr} = 1.049 \times 10^3 \frac{kg}{s^2}$$

Plate characteristics for simple bending for shore grade 85 at 60 ºC

Youngs Modulus $E := 6.5025MPa$

Possion ratio $v := 0.47$

Radius of Plate $R := 0.10487m$

Thickness of Plate $H := 0.01m$

Mid Plate thickness $h := \frac{H}{2}$

Uniform Pressure $P := 0.02MPa$

Radius at the Edge $r := 0mm$

1 - Maximum Deflection at center for r = 0

A - CALCULATIONS

$$D := \frac{2.E \cdot h^3}{3(1 - v^2)}$$

$$D = 0.696 J$$

The general deflection equation for simple support is given by:

$$W_{max} := \frac{P \cdot R^4}{64.D}\left(\frac{5 + v}{1 + v}\right)$$

$$W_{max} = 0.202 m$$

2 - Bending Moment along the r-axis at center for r = 0

B - CALCULATIONS

$$M_{rr} := \frac{P}{16}(3 + v)(R^2 - r^2)$$

$$M_{rr} = 47.703 N$$

3 - Bending Moment along the Θ -axis at center for r = 0

C - CALCULATIONS

$$M_{\Theta\Theta} := \frac{P}{16}\left[(1 + v)R^2 - (1 + 3v)r^2\right]$$

$$M_{\Theta\Theta} = 20.208 N$$

4 - Shear stress at r=R

D - CALCULATIONS

The general equation for shear force is given by

$$S_{rr} := \frac{P \cdot R}{2}$$

$$S_{rr} = 1.049 \times 10^3 \frac{kg}{s^2}$$

Plate characteristics for simple bending for shore grade 85 at 70 ºC

Youngs Modulus	$E := 5.4672MPa$
Possion ratio	$v := 0.47$
Radius of Plate	$R := 0.10487m$
Thickness of Plate	$H := 0.01m$
Mid Plate thickness	$h := \frac{H}{2}$
Uniform Pressure	$P := 0.02MPa$
Radius at the Edge	$r := 0mm$

1 - Maximum Deflection at center for r = 0

A - CALCULATIONS

$$D := \frac{2.E \cdot h^3}{3\left(1 - v^2\right)}$$

$$D = 0.585\,J$$

The general deflection equation for simple support is given by:

$$W_{max} := \frac{P \cdot R^4}{64.D}\left(\frac{5 + v}{1 + v}\right)$$

$$W_{max} = 0.241\,m$$

2 - Bending Moment along the r-axis at center for r = 0

B - CALCULATIONS

$$M_{rr} := \frac{P}{16}(3 + v)\left(R^2 - r^2\right)$$

$$M_{rr} = 47.703\,N$$

3 - Bending Moment along the Θ -axis at center for r = 0

C - CALCULATIONS

$$M_{\Theta\Theta} := \frac{P}{16}\left[(1 + v)R^2 - (1 + 3v)r^2\right]$$

$$M_{\Theta\Theta} = 20.208\,N$$

4 - Shear stress at r=R

D - CALCULATIONS

The general equation for shear force is given by

$$S_{rr} := \frac{P \cdot R}{2}$$

$$S_{rr} = 1.049 \times 10^3 \frac{kg}{s^2}$$

Plate characteristics for simple bending for shore grade 85 at 80 ºC

Youngs Modulus $E := 5.2399MPa$

Possion ratio $v := 0.47$

Radius of Plate $R := 0.10487m$

Thickness of Plate $H := 0.01m$

Mid Plate thickness $h := \frac{H}{2}$

Uniform Pressure $P := 0.02MPa$

Radius at the Edge $r := 0mm$

1 - Maximum Deflection at center for r = 0

A - CALCULATIONS

$$D := \frac{2.E \cdot h^3}{3\left(1 - v^2\right)}$$

$$D = 0.56\,J$$

The general deflection equation for simple support is given by:

$$W_{max} := \frac{P \cdot R^4}{64.D}\left(\frac{5 + v}{1 + v}\right)$$

$$W_{max} = 0.251\,m$$

2 - Bending Moment along the r-axis at center for r = 0

B - CALCULATIONS

$$M_{rr} := \frac{P}{16}(3 + v)\left(R^2 - r^2\right)$$

$$M_{rr} = 47.703\,N$$

3 - Bending Moment along the Θ -axis at center for r = 0

C - CALCULATIONS

$$M_{\Theta\Theta} := \frac{P}{16}\left[(1 + v)R^2 - (1 + 3v)r^2\right]$$

$$M_{\Theta\Theta} = 20.208\,N$$

4 - Shear stress at r=R

D - CALCULATIONS

The general equation for shear force is given by

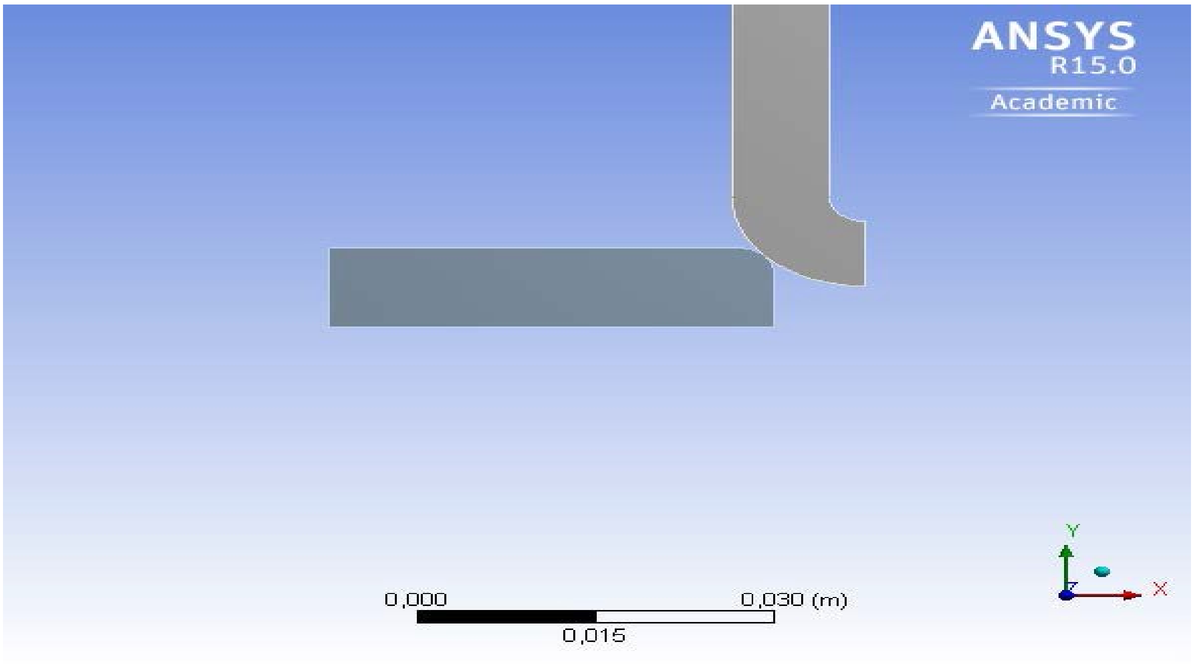
$$S_{rr} := \frac{P \cdot R}{2}$$

$$S_{rr} = 1.049 \times 10^3 \frac{kg}{s^2}$$

Appendix 6 Reaction force for static analysis - typical

Project - Shore Grade 65 at 20°C

First Saved	Saturday, May 02, 2015
Last Saved	Saturday, May 23, 2015
Product Version	15.0 Release
Imported Source	C:\Temp\thesis\ANDREW_Mechdat-file-to-Open-in-ANSYS_\Mechdat-to-ANDREW\Axisymmetry_ITR-02.mechdat
Imported Version	14.0 Release
Save Project Before Solution	No
Save Project After Solution	No



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PU_STRESS-STRAIN

Units

TABLE 1

Unit System	Metric (m, kg, N, s, V, A) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	Rad/s
Temperature	Celsius

Model (A4)

Geometry

TABLE 2
Model (A4) > Geometry

Object Name	*Geometry*
State	Fully Defined
Definition	
Source	C:\Andrew_Youtube\ANSYS_NEW\PIPE_AXISYMMETRY_files\dp0\SYS-1\DM\SYS-1.agdb
Type	DesignModeler

Length Unit	Millimeters
Element Control	Program Controlled
2D Behavior	Axisymmetric
Display Style	Body Color
Bounding Box	
Length X	4,505e-002 m
Length Y	4,338e-002 m
Properties	

Volume	0, m³
Mass	
Surface Area(approx.)	6,8373e-004 m²
Scale Factor Value	1,
Statistics	
Bodies	2
Active Bodies	2
Nodes	2283
Elements	699
Mesh Metric	None
Basic Geometry Options	
Parameters	Yes
Parameter Key	DS
Attributes	No
Named Selections	No
Material Properties	No
Advanced Geometry Options	
Use Associativity	Yes
Coordinate Systems	No
Reader Mode Saves Updated File	No
Use Instances	Yes
Smart CAD Update	No
Compare Parts On Update	No
Attach File Via Temp File	Yes
Temporary Directory	C:\Users\222982\AppData\Roaming\Ansys\v150
Analysis Type	2-D
Decompose Disjoint Geometry	Yes
Enclosure and Symmetry Processing	Yes

TABLE 3

Model (A4) > Geometry > Parts

Object Name	*PIPE-SIMPLIFIED_AXI*	*PIPE-SIMPLIFIED_AXI*

State	Meshed	
Graphics Properties		
Visible	Yes	
Transparency	1	
Definition		
Suppressed	No	
Stiffness Behavior	Flexible	
Coordinate System	Default Coordinate System	
Reference Temperature	By Environment	
Material		
Assignment	Structural Steel	PU_STRESS-STRAIN
Nonlinear Effects	Yes	
Thermal Strain Effects	Yes	
Bounding Box		

Length X	1,118e-002 m	3,737e-002 m
Length Y	3,818e-002 m	1,e-002 m
Properties		
Volume	N/A	
Mass	N/A	
Centroid X	N/A	
Centroid Y	N/A	
Centroid Z	N/A	
Moment of Inertia Ip1	N/A	
Moment of Inertia Ip2	N/A	
Moment of Inertia Ip3	N/A	
Surface Area(approx.)	3,1196e-004 m²	3,7177e-004 m²
Statistics		
Nodes	1065	1218
Elements	324	375
Mesh Metric	None	

Coordinate Systems

TABLE 4
Model (A4) > Coordinate Systems > Coordinate System

Object Name	*Global Coordinate System*
State	Fully Defined
Definition	
Type	Cartesian
Coordinate System ID	0,
Origin	
Origin X	0, m
Origin Y	0, m
Directional Vectors	
X Axis Data	[1, 0,]
Y Axis Data	[0, 1,]

Connections

TABLE 5
Model (A4) > Connections

Object Name	*Connections*
State	Fully Defined
Auto Detection	
Generate Automatic Connection On Refresh	Yes
Transparency	
Enabled	Yes

TABLE 6
Model (A4) > Connections > Contacts

Object Name	*Contacts*
State	Fully Defined
Definition	
Connection Type	Contact
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Auto Detection	
Tolerance Type	Slider
Tolerance Slider	0,
Tolerance Value	1,5635e-004 m
Use Range	No
Face/Edge	No
Edge/Edge	Yes
Priority	Include All
Group By	Bodies
Search Across	Bodies

TABLE 7
Model (A4) > Connections > Contacts > Contact Regions

Object Name	*Frictional - PIPE-SIMPLIFIED_AXI To PIPE-SIMPLIFIED_AXI*
State	Fully Defined
Scope	
Scoping Method	Geometry Selection
Contact	3 Edges
Target	2 Edges
Contact Bodies	PIPE-SIMPLIFIED_AXI
Target Bodies	PIPE-SIMPLIFIED_AXI
Shell Thickness Effect	No
Definition	
Type	Frictional
Friction Coefficient	0,15
Scope Mode	Manual

Behavior	Asymmetric
Trim Contact	Program Controlled
Suppressed	No
Advanced	
Formulation	Augmented Lagrange
Detection Method	Nodal-Normal To Target
Penetration Tolerance	Program Controlled
Elastic Slip Tolerance	Program Controlled
Normal Stiffness	Manual
Normal Stiffness Factor	0,1
Update Stiffness	Each Iteration
Stabilization Damping Factor	0,
Pinball Region	Radius
Pinball Radius	2,e-003 m
Time Step Controls	None
Geometric Modification	
Interface Treatment	Add Offset, No Ramping
Offset	0, m
Contact Geometry Correction	None

Mesh

TABLE 8

Model (A4) > Mesh

Object Name	*Mesh*
State	Solved
Defaults	
Physics Preference	Mechanical
Relevance	0
Sizing	
Use Advanced Size Function	On: Curvature
Relevance Center	Coarse
Initial Size Seed	Active Assembly
Smoothing	Medium
Span Angle Center	Coarse
Curvature Normal Angle	Default (30,0 °)
Min Size	Default (4,6207e-004 m)
Max Face Size	Default (2,3104e-003 m)
Growth Rate	Default
Minimum Edge Length	4,7124e-003 m
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0,272
Maximum Layers	2
Growth Rate	1,2
Inflation Algorithm	Pre

View Advanced Options	No
Patch Conforming Options	
Triangle Surface Mesher	Program Controlled
Patch Independent Options	
Topology Checking	Yes
Advanced	
Number of CPUs for Parallel Part Meshing	Program Controlled
Shape Checking	Standard Mechanical
Element Midside Nodes	Kept
Number of Retries	Default (4)
Extra Retries For Assembly	Yes
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Defeaturing	
Use Sheet Thickness for Pinch	No
Pinch Tolerance	Default (4,1586e-004 m)
Generate Pinch on Refresh	No
Sheet Loop Removal	No
Automatic Mesh Based Defeaturing	On
Defeaturing Tolerance	Default (3,4655e-004 m)
Statistics	
Nodes	2283
Elements	699
Mesh Metric	None

TABLE 9
Model (A4) > Mesh > Mesh Controls

Object Name	*Body Sizing*
State	Fully Defined
Scope	
Scoping Method	Geometry Selection
Geometry	2 Bodies
Definition	
Suppressed	No
Type	Element Size
Element Size	1,e-003 m
Behavior	Soft
Curvature Normal Angle	Default
Growth Rate	Default
Local Min Size	Default (4,6207e-004 m)

Static Structural (A5)

TABLE 10
Model (A4) > Analysis

Object Name	*Static Structural (A5)*

State	Solved
Definition	
Physics Type	Structural
Analysis Type	Static Structural
Solver Target	Mechanical APDL
Options	
Environment Temperature	22, °C
Generate Input Only	No

TABLE 11
Model (A4) > Static Structural (A5) > Analysis Settings

Object Name	*Analysis Settings*
State	Fully Defined
Step Controls	
Number Of Steps	6,
Current Step Number	1,
Step End Time	1, s
Auto Time Stepping	On
Define By	Substeps
Initial Substeps	100,
Minimum Substeps	50,
Maximum Substeps	200,
Solver Controls	
Solver Type	Direct
Weak Springs	Off
Large Deflection	On
Inertia Relief	Off
Restart Controls	
Generate Restart Points	Program Controlled
Retain Files After Full Solve	No
Nonlinear Controls	
Newton-Raphson Option	Program Controlled
Force Convergence	Program Controlled
Moment Convergence	Program Controlled
Displacement Convergence	Program Controlled
Rotation Convergence	Program Controlled
Line Search	Program Controlled
Stabilization	Off
Output Controls	
Stress	Yes
Strain	Yes
Nodal Forces	Yes
Contact Miscellaneous	No
General Miscellaneous	No
Store Results At	All Time Points
Analysis Data Management	
Solver Files Directory	C:\Temp\thesis\Static analysis_files\dp0\SYS\MECH\

Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	No
Delete Unneeded Files	Yes
Nonlinear Solution	Yes
Solver Units	Active System
Solver Unit System	mks

TABLE 12
Model (A4) > Static Structural (A5) > Analysis Settings
Step-Specific "Step Controls"

Step	Step End Time	Carry Over Time Step
1	1, s	
2	2, s	Off
3	3, s	
4	4, s	
5	5, s	
6	6, s	

TABLE 13
Model (A4) > Static Structural (A5) > Loads

Object Name	*Displacement*	*Displacement 2*
State	Fully Defined	
Scope		
Scoping Method	Geometry Selection	
Geometry	1 Edge	
Definition		
Type	Displacement	
Define By	Components	
Coordinate System	Global Coordinate System	
X Component	0, m (ramped)	
Y Component	0, m (ramped)	Tabular Data
Suppressed	No	
Tabular Data		
Independent Variable		Time

FIGURE 1
Model (A4) > Static Structural (A5) > Displacement

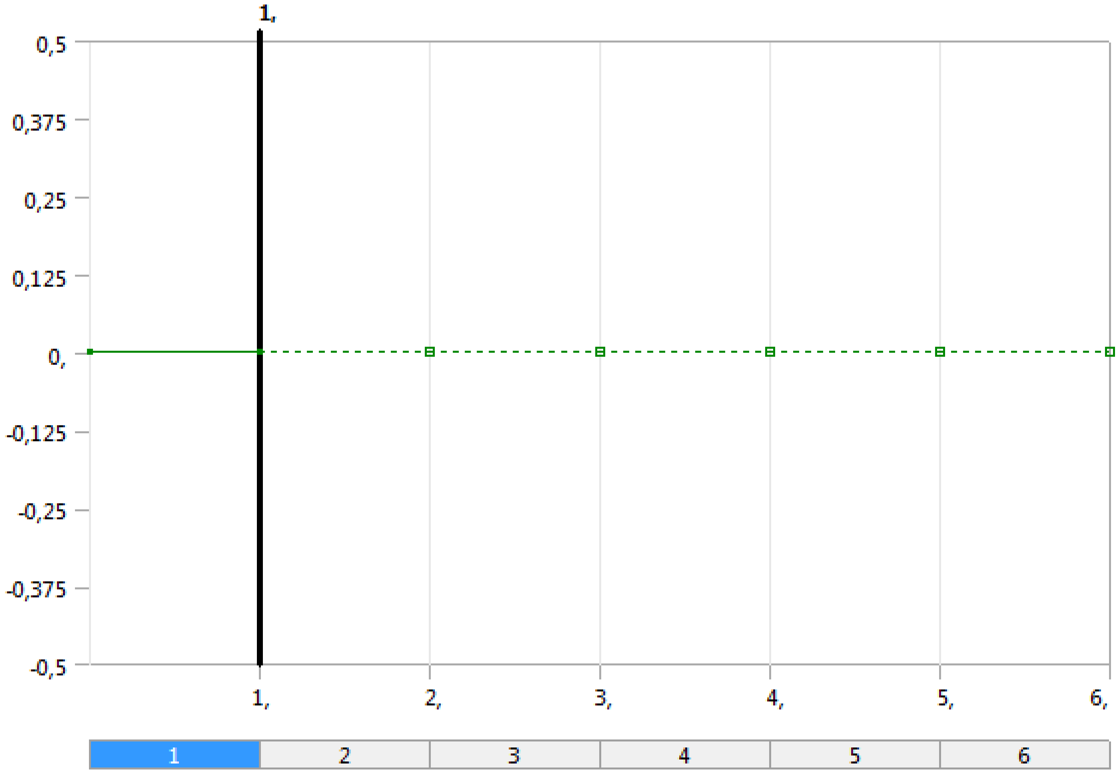

FIGURE 2
Model (A4) > Static Structural (A5) > Displacement 2

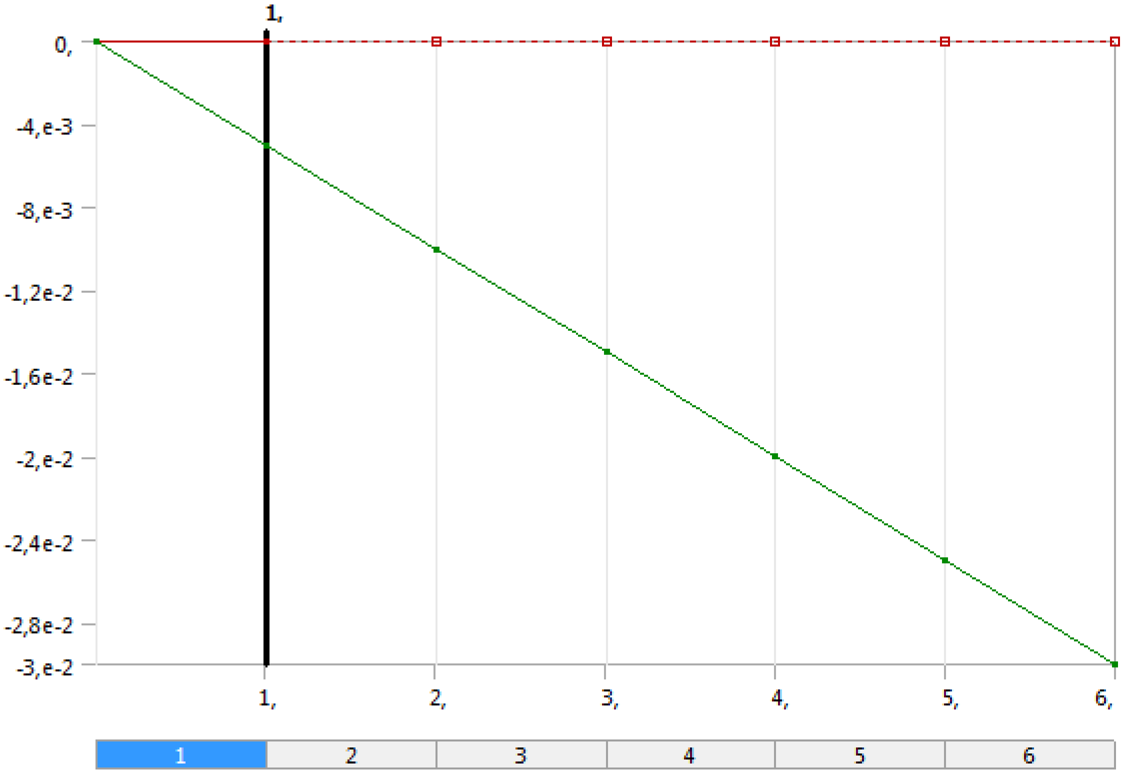

TABLE 14
Model (A4) > Static Structural (A5) > Displacement 2

Steps	Time [s]	X [m]	Y [m]
1	0,	0,	0,
	1,		-5,e-003
2	2,	= 0,	-1,e-002
3	3,		-1,5e-002
4	4,		-2,e-002
5	5,		-2,5e-002
6	6,		-3,e-002

Solution (A6)

TABLE 15
Model (A4) > Static Structural (A5) > Solution

Object Name	*Solution (A6)*
State	Solved
Adaptive Mesh Refinement	
Max Refinement Loops	1,
Refinement Depth	2,
Information	
Status	Done

TABLE 16
Model (A4) > Static Structural (A5) > Solution (A6) > Solution Information

Object Name	*Solution Information*
State	Solved
Solution Information	
Solution Output	Force Convergence
Newton-Raphson Residuals	0
Update Interval	2,5 s
Display Points	All
FE Connection Visibility	
Activate Visibility	Yes
Display	All FE Connectors
Draw Connections Attached To	All Nodes
Line Color	Connection Type
Visible on Results	No
Line Thickness	Single
Display Type	Lines

FIGURE 3
Model (A4) > Static Structural (A5) > Solution (A6) > Solution Information

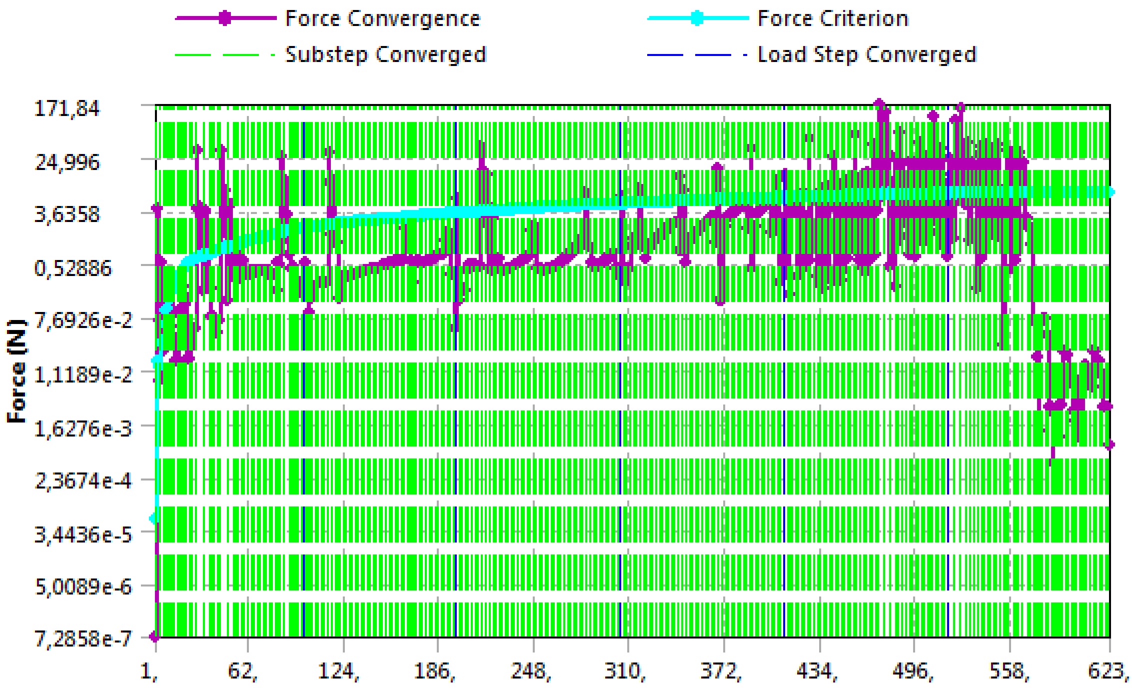

FIGURE 4
Model (A4) > Static Structural (A5) > Solution (A6) > Solution Information

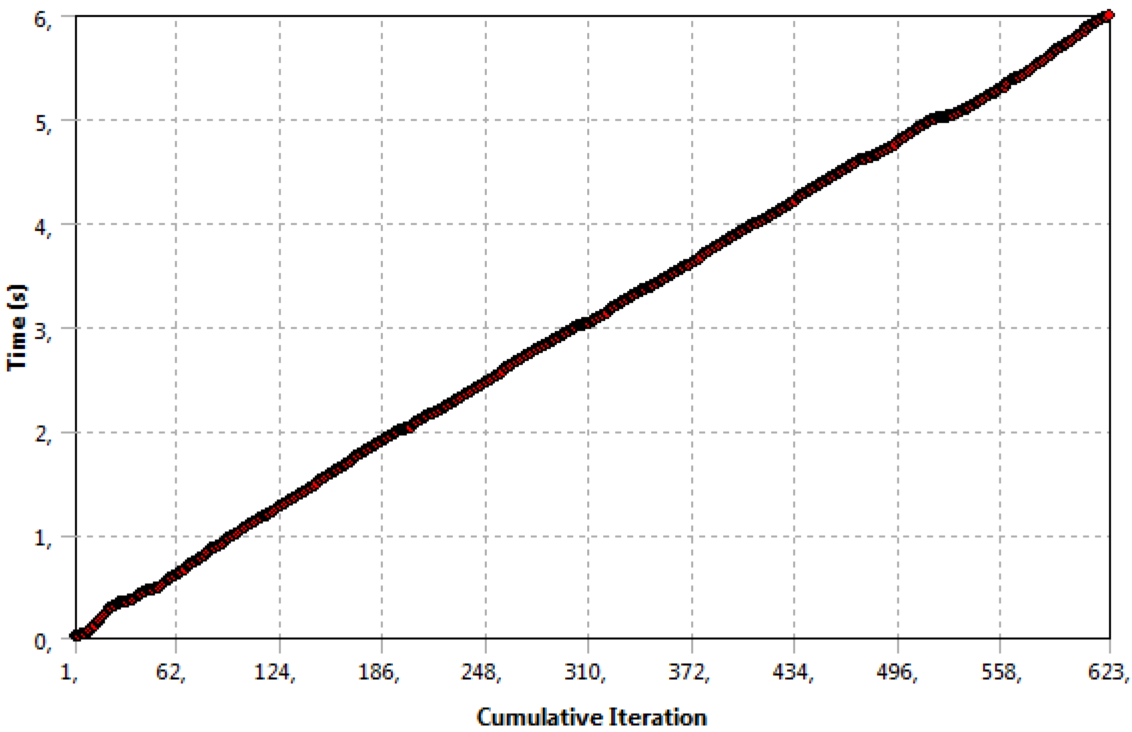

TABLE 17
Model (A4) > Static Structural (A5) > Solution (A6) > Results

Object Name	*Total Deformation*	*Equivalent Elastic Strain*
State	Solved	
Scope		
Scoping Method	Geometry Selection	
Geometry	All Bodies	
Definition		
Type	Total Deformation	Equivalent Elastic Strain
By	Time	
Display Time	6, s	Last
Calculate Time History	Yes	
Identifier		
Suppressed	No	
Results		
Minimum	0, m	6,4558e-008 m/m
Maximum	3,e-002 m	0,33297 m/m
Minimum Occurs On	PIPE-SIMPLIFIED_AXI	
Maximum Occurs On	PIPE-SIMPLIFIED_AXI	
Minimum Value Over Time		
Minimum	0, m	0, m/m
Maximum	0, m	2,5664e-007 m/m
Maximum Value Over Time		
Minimum	5,e-005 m	1,2317e-014 m/m
Maximum	3,e-002 m	0,33475 m/m
Information		
Time	6, s	
Load Step	6	
Substep	52	
Iteration Number	623	
Integration Point Results		
Display Option		Averaged
Average Across Bodies		No

FIGURE 5
Model (A4) > Static Structural (A5) > Solution (A6) > Total Deformation

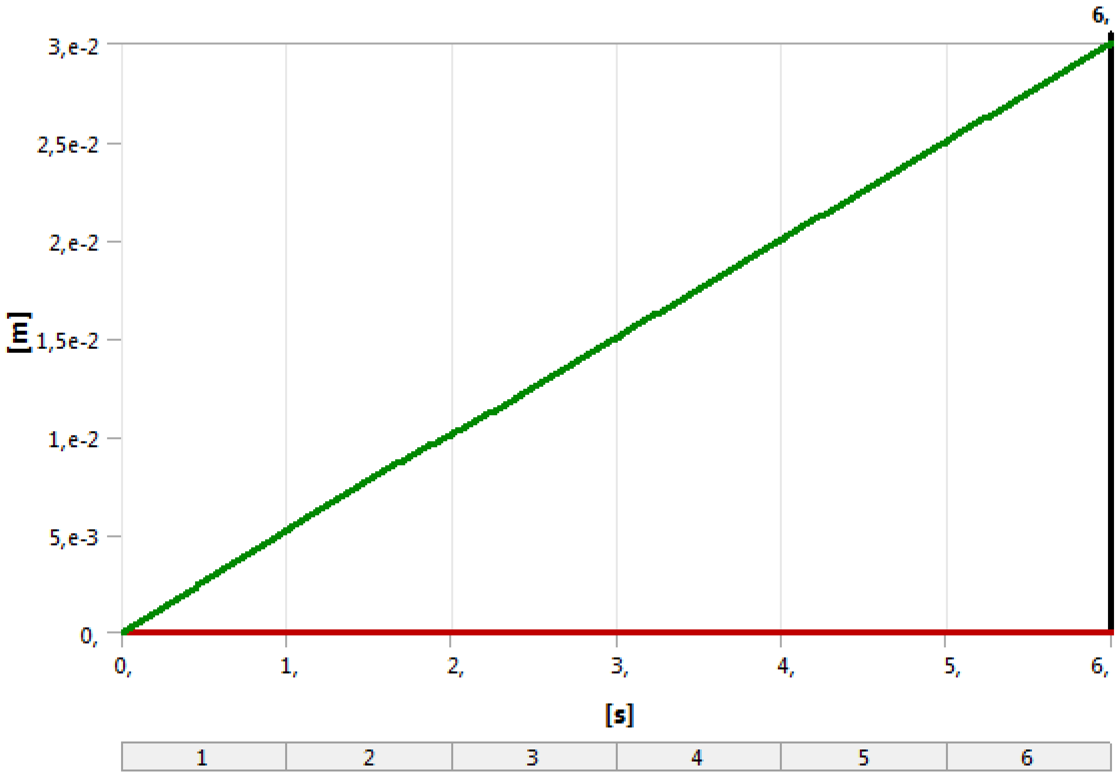

TABLE 18
Model (A4) > Static Structural (A5) > Solution (A6) > Total Deformation

Time [s]	Minimum [m]	Maximum [m]
1,e-002	0,	5,e-005
2,e-002		1,e-004
3,e-002		1,5e-004
4,5e-002		2,25e-004
6,5e-002		3,25e-004
8,5e-002		4,25e-004
0,105		5,25e-004
0,125		6,25e-004
0,145		7,25e-004
0,165		8,25e-004
0,185		9,25e-004
0,205		1,025e-003
0,225		1,125e-003
0,245		1,225e-003
0,265		1,325e-003
0,285		1,425e-003
0,305		1,525e-003
0,325		1,625e-003
0,345		1,7473e-003
0,365		1,8511e-003
0,385		1,9542e-003
0,405		2,0571e-003
0,425		2,1599e-003

0,445		2,2626e-003
0,465		2,4041e-003
0,485		2,5067e-003

0,505		2,6092e-003
0,525		2,7136e-003
0,545		2,8201e-003
0,565		2,926e-003
0,585		3,0309e-003
0,605		3,136e-003
0,625		3,2408e-003
0,645		3,3455e-003
0,665		3,45e-003
0,685		3,5543e-003
0,705		3,6585e-003
0,725		3,7625e-003
0,745		3,8662e-003
0,765		3,9699e-003
0,785		4,0751e-003
0,805		4,1795e-003
0,825		4,2833e-003
0,845		4,3871e-003
0,865		4,5006e-003
0,885		4,6076e-003
0,905		4,7105e-003
0,925		4,8137e-003
0,945		4,917e-003
0,965		5,0201e-003
0,985		5,1231e-003
1,		5,2004e-003
1,01		5,2516e-003
1,02		5,3031e-003
1,035		5,3803e-003
1,055		5,4831e-003
1,075		5,5858e-003
1,095		5,6884e-003
1,115		5,7909e-003
1,135		5,8933e-003
1,155		5,9957e-003
1,175		6,1078e-003
1,195		6,2112e-003
1,215		6,3132e-003
1,235		6,4154e-003
1,255		6,5176e-003
1,275		6,6197e-003
1,295		6,7217e-003
1,315		6,8235e-003
1,335		6,9253e-003
1,355		7,027e-003

1,375		7,1286e-003
1,395		7,2301e-003
1,415		7,3314e-003
1,435		7,4327e-003
1,455		7,5338e-003
1,475		7,6347e-003
1,495		7,7354e-003
1,515		7,8359e-003
1,535		7,9363e-003
1,555		8,0366e-003
1,575		8,1367e-003
1,595		8,2367e-003
1,615		8,3365e-003
1,635		8,4362e-003
1,655		8,5357e-003
1,675		8,6317e-003
1,695		8,7242e-003
1,715		8,8162e-003
1,735		8,9084e-003
1,755		9,0004e-003
1,775		9,0918e-003
1,795		9,1831e-003
1,815		9,274e-003
1,835		9,3647e-003
1,855		9,4552e-003
1,875		9,5453e-003
1,895		9,6352e-003
1,915		9,7249e-003
1,935		9,8142e-003
1,955		9,9033e-003
1,975		9,9922e-003
1,9875		1,0048e-002
2,		1,0103e-002
2,01		1,0147e-002
2,02		1,0191e-002
2,035		1,0257e-002
2,055		1,0345e-002
2,075		1,0433e-002
2,095		1,052e-002
2,115		1,0608e-002
2,135		1,0694e-002
2,155		1,0803e-002
2,175		1,0887e-002
2,195		1,0975e-002
2,215		1,1075e-002
2,235		1,1175e-002
2,255		1,1275e-002
2,275		1,1375e-002

2,295		1,1475e-002
2,315		1,1575e-002
2,335		1,1675e-002
2,355		1,1775e-002
2,375		1,1875e-002
2,395		1,1975e-002
2,415		1,2075e-002
2,435		1,2175e-002
2,455		1,2275e-002
2,475		1,2375e-002
2,495		1,2475e-002

2,515		1,2575e-002
2,535		1,2675e-002
2,555		1,2775e-002
2,575		1,2875e-002
2,595		1,2975e-002
2,615		1,3075e-002
2,635		1,3175e-002
2,655		1,3275e-002
2,675		1,3375e-002
2,695		1,3475e-002
2,715		1,3575e-002
2,735		1,3675e-002
2,755		1,3775e-002
2,775		1,3875e-002
2,795		1,3975e-002
2,815		1,4075e-002
2,835		1,4175e-002
2,855		1,4275e-002
2,875		1,4375e-002
2,895		1,4475e-002
2,915		1,4575e-002
2,935		1,4675e-002
2,955		1,4775e-002
2,975		1,4875e-002
2,9875		1,4938e-002
3,		1,5e-002
3,01		1,505e-002
3,02		1,51e-002
3,035		1,5175e-002
3,055		1,5275e-002
3,075		1,5375e-002
3,095		1,5475e-002
3,115		1,5575e-002
3,135		1,5675e-002
3,155		1,5775e-002
3,175		1,5875e-002
3,195		1,5975e-002

3,215		1,6075e-002
3,235		1,6175e-002
3,255		1,6275e-002
3,275		1,6375e-002
3,295		1,6475e-002
3,315		1,6575e-002
3,335		1,6675e-002
3,355		1,6775e-002
3,375		1,6875e-002
3,395		1,6975e-002
3,415		1,7075e-002
3,435		1,7175e-002
3,455		1,7275e-002
3,475		1,7375e-002
3,495		1,7475e-002

3,515		1,7575e-002
3,535		1,7675e-002
3,555		1,7775e-002
3,575		1,7875e-002
3,595		1,7975e-002
3,615		1,8075e-002
3,635		1,8175e-002
3,655		1,8275e-002
3,675		1,8375e-002
3,695		1,8475e-002
3,715		1,8575e-002
3,735		1,8675e-002
3,755		1,8775e-002
3,775		1,8875e-002
3,795		1,8975e-002
3,815		1,9075e-002
3,835		1,9175e-002
3,855		1,9275e-002
3,875		1,9375e-002
3,895		1,9475e-002
3,915		1,9575e-002
3,935		1,9675e-002
3,955		1,9775e-002
3,975		1,9875e-002
3,9875		1,9938e-002
4,		2,e-002
4,01		2,005e-002
4,02		2,01e-002
4,035		2,0175e-002
4,055		2,0275e-002
4,075		2,0375e-002
4,095		2,0475e-002
4,115		2,0575e-002

4,135		2,0675e-002
4,155		2,0775e-002
4,175		2,0875e-002
4,195		2,0975e-002
4,215		2,1075e-002
4,235		2,1175e-002
4,255		2,1275e-002
4,275		2,1375e-002
4,295		2,1475e-002
4,315		2,1575e-002
4,335		2,1675e-002
4,355		2,1775e-002
4,375		2,1875e-002
4,395		2,1975e-002
4,415		2,2075e-002
4,435		2,2175e-002
4,455		2,2275e-002
4,475		2,2375e-002
4,495		2,2475e-002
4,515		2,2575e-002
4,535		2,2675e-002
4,555		2,2775e-002
4,575		2,2875e-002
4,595		2,2975e-002
4,615		2,3075e-002
4,635		2,3175e-002
4,655		2,3275e-002
4,675		2,3375e-002
4,695		2,3475e-002
4,715		2,3575e-002
4,735		2,3675e-002
4,755		2,3775e-002
4,775		2,3875e-002
4,795		2,3975e-002
4,815		2,4075e-002
4,835		2,4175e-002
4,855		2,4275e-002
4,875		2,4375e-002
4,895		2,4475e-002
4,915		2,4575e-002
4,935		2,4675e-002
4,955		2,4775e-002
4,975		2,4875e-002
4,9875		2,4938e-002
5,		2,5e-002
5,01		2,505e-002
5,02		2,51e-002
5,035		2,5175e-002

5,055		2,5275e-002
5,075		2,5375e-002
5,095		2,5475e-002
5,115		2,5575e-002
5,135		2,5675e-002
5,155		2,5775e-002
5,175		2,5875e-002
5,195		2,5975e-002
5,215		2,6075e-002
5,235		2,6175e-002
5,255		2,6275e-002
5,275		2,6375e-002
5,295		2,6475e-002
5,315		2,6575e-002
5,335		2,6675e-002
5,355		2,6775e-002
5,375		2,6875e-002
5,395		2,6975e-002
5,415		2,7075e-002
5,435		2,7175e-002
5,455		2,7275e-002
5,475		2,7375e-002
5,495		2,7475e-002

5,515		2,7575e-002
5,535		2,7675e-002
5,555		2,7775e-002
5,575		2,7875e-002
5,595		2,7975e-002
5,615		2,8075e-002
5,635		2,8175e-002
5,655		2,8275e-002
5,675		2,8375e-002
5,695		2,8475e-002
5,715		2,8575e-002
5,735		2,8675e-002
5,755		2,8775e-002
5,775		2,8875e-002
5,795		2,8975e-002
5,815		2,9075e-002
5,835		2,9175e-002
5,855		2,9275e-002
5,875		2,9375e-002
5,895		2,9475e-002
5,915		2,9575e-002
5,935		2,9675e-002
5,955		2,9775e-002
5,975		2,9875e-002

5,9875		2,9938e-002
6,		3,e-002

FIGURE 6
Model (A4) > Static Structural (A5) > Solution (A6) > Equivalent Elastic Strain

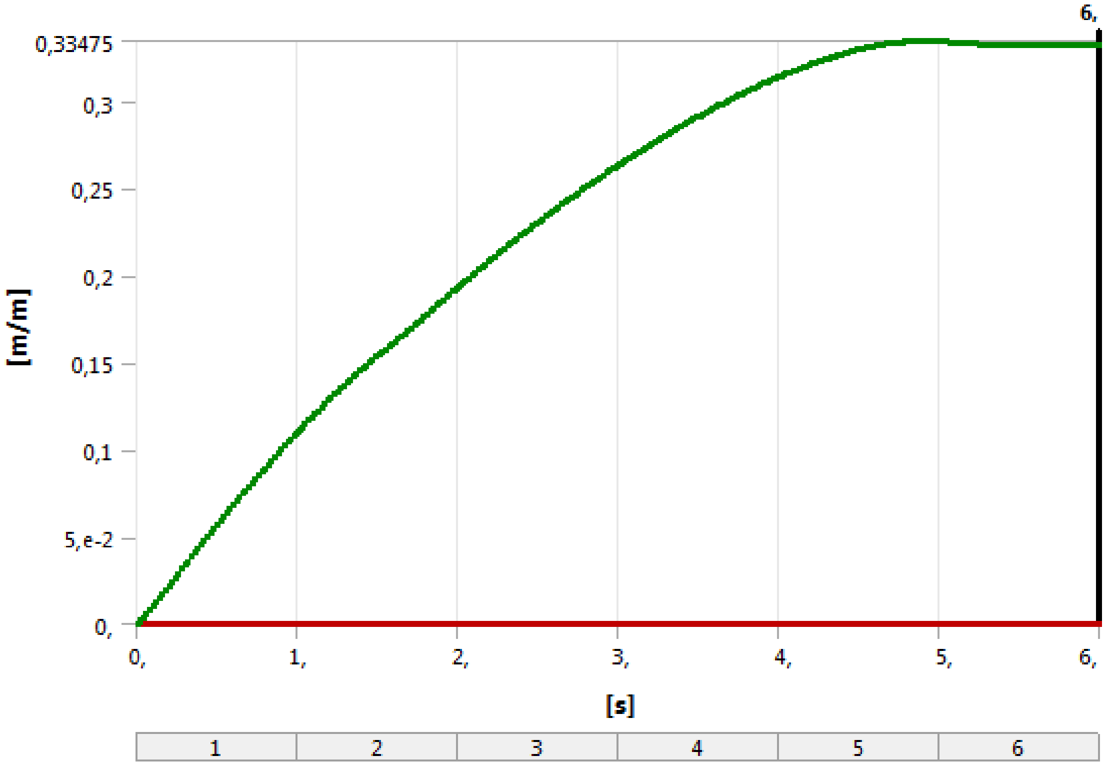

TABLE 19
Model (A4) > Static Structural (A5) > Solution (A6) > Equivalent Elastic Strain

Time [s]	Minimum [m/m]	Maximum [m/m]
1,e-002	0,	1,2317e-014
2,e-002	3,5334e-010	7,9705e-004
3,e-002	1,3329e-009	1,9155e-003
4,5e-002	2,5207e-009	3,6418e-003
6,5e-002	4,1168e-009	5,973e-003
8,5e-002	5,7012e-009	8,2979e-003
0,105	7,2713e-009	1,0614e-002
0,125	8,8254e-009	1,2921e-002
0,145	1,0361e-008	1,5215e-002
0,165	1,1875e-008	1,7491e-002
0,185	1,3367e-008	1,975e-002
0,205	1,4899e-008	2,2076e-002
0,225	1,6421e-008	2,44e-002
0,245	1,7929e-008	2,6715e-002
0,265	1,9423e-008	2,9024e-002
0,285	2,0897e-008	3,1317e-002
0,305	2,2352e-008	3,3595e-002
0,325	2,3791e-008	3,5859e-002

0,345	2,5753e-008	3,8935e-002
0,365	2,715e-008	4,1162e-002
0,385	2,8534e-008	4,3383e-002
0,405	2,9901e-008	4,5591e-002
0,425	3,1253e-008	4,7786e-002
0,445	3,2589e-008	4,9968e-002
0,465	3,4418e-008	5,2922e-002
0,485	3,572e-008	5,5069e-002
0,505	3,7023e-008	5,7238e-002
0,525	3,8349e-008	5,9462e-002
0,545	3,9661e-008	6,1658e-002
0,565	4,0955e-008	6,3824e-002
0,585	4,2237e-008	6,5998e-002
0,605	4,3509e-008	6,8164e-002
0,625	4,4767e-008	7,0316e-002
0,645	4,6013e-008	7,246e-002
0,665	4,7247e-008	7,4594e-002
0,685	4,8469e-008	7,6717e-002
0,705	4,9679e-008	7,8831e-002
0,725	5,0877e-008	8,0934e-002
0,745	5,2064e-008	8,3028e-002
0,765	5,3241e-008	8,5113e-002
0,785	5,4448e-008	8,7235e-002
0,805	5,564e-008	8,9326e-002
0,825	5,6819e-008	9,1417e-002
0,845	5,7988e-008	9,3511e-002
0,865	5,9359e-008	9,618e-002
0,885	6,0521e-008	9,8151e-002
0,905	6,1647e-008	0,10018
0,925	6,2772e-008	0,10222
0,945	6,389e-008	0,10423
0,965	6,4999e-008	0,10622
0,985	6,6101e-008	0,1082
1,	6,6925e-008	0,10967
1,01	6,7471e-008	0,11062
1,02	6,8018e-008	0,1116
1,035	6,8836e-008	0,11305
1,055	6,9924e-008	0,11496
1,075	7,1011e-008	0,11685
1,095	7,2097e-008	0,11872
1,115	7,3184e-008	0,12057
1,135	7,4273e-008	0,1224
1,155	7,5365e-008	0,12421
1,175	7,6491e-008	0,12671
1,195	7,7572e-008	0,12851
1,215	7,8649e-008	0,13027
1,235	7,9735e-008	0,13201
1,255	8,0827e-008	0,13374

1,275	8,1928e-008	0,13546
1,295	8,3039e-008	0,13715
1,315	8,4162e-008	0,13883
1,335	8,5297e-008	0,14049
1,355	8,6447e-008	0,14213
1,375	8,7612e-008	0,14376
1,395	8,8793e-008	0,14536
1,415	8,9993e-008	0,14696
1,435	9,1212e-008	0,14853
1,455	9,2453e-008	0,15009
1,475	9,3711e-008	0,15164
1,495	9,4988e-008	0,15317
1,515	9,3512e-008	0,15469
1,535	9,0007e-008	0,15619
1,555	8,6323e-008	0,15768
1,575	8,2464e-008	0,15915
1,595	7,8431e-008	0,16061
1,615	7,423e-008	0,16206
1,635	6,9864e-008	0,16349
1,655	6,534e-008	0,16492
1,675	6,3236e-008	0,16644
1,695	6,415e-008	0,1681
1,715	6,5502e-008	0,16977
1,735	6,6568e-008	0,17144
1,755	6,7679e-008	0,17309
1,775	6,8809e-008	0,17473
1,795	6,9936e-008	0,17637
1,815	7,1085e-008	0,178
1,835	7,225e-008	0,17962
1,855	7,3431e-008	0,18124
1,875	7,4628e-008	0,18285
1,895	7,584e-008	0,18445
1,915	7,707e-008	0,18604
1,935	7,8316e-008	0,18763
1,955	7,9579e-008	0,18921
1,975	8,0859e-008	0,19079

1,9875	8,1737e-008	0,19177
2,	8,2655e-008	0,19276
2,01	8,3261e-008	0,19355
2,02	8,4019e-008	0,19434
2,035	8,5091e-008	0,19551
2,055	8,6495e-008	0,19708
2,075	8,7939e-008	0,19863
2,095	8,9416e-008	0,20018
2,115	9,0912e-008	0,20172
2,135	9,2426e-008	0,20326
2,155	9,1067e-008	0,20496
2,175	9,5656e-008	0,20661

2,195	9,6852e-008	0,20811
2,215	9,8057e-008	0,2096
2,235	9,9653e-008	0,2111
2,255	1,0131e-007	0,21259
2,275	1,0297e-007	0,21407
2,295	1,0464e-007	0,21555
2,315	1,0634e-007	0,21702
2,335	1,0806e-007	0,21849
2,355	1,098e-007	0,21994
2,375	1,1157e-007	0,22139
2,395	1,1335e-007	0,22283
2,415	1,1516e-007	0,22427
2,435	1,1699e-007	0,2257
2,455	1,1885e-007	0,22712
2,475	1,2073e-007	0,22853
2,495	1,2263e-007	0,22994
2,515	1,2456e-007	0,23134
2,535	1,2651e-007	0,23273
2,555	1,2848e-007	0,23412
2,575	1,3048e-007	0,2355
2,595	1,3251e-007	0,23687
2,615	1,3456e-007	0,23823
2,635	1,3664e-007	0,23959
2,655	1,3875e-007	0,24094
2,675	1,4088e-007	0,24228
2,695	1,4304e-007	0,24362
2,715	1,4523e-007	0,24495
2,735	1,4745e-007	0,24627
2,755	1,4969e-007	0,24758
2,775	1,5196e-007	0,24889
2,795	1,5426e-007	0,25019
2,815	1,5665e-007	0,25149
2,835	1,5896e-007	0,25277
2,855	1,6032e-007	0,25405
2,875	1,6109e-007	0,25532
2,895	1,6187e-007	0,25658
2,915	1,6264e-007	0,25784
2,935	1,6341e-007	0,25909
2,955	1,6418e-007	0,26033
2,975	1,6494e-007	0,26156

2,9875	1,6541e-007	0,26233
3,	1,6589e-007	0,2631
3,01	1,6628e-007	0,2637
3,02	1,6665e-007	0,26431
3,035	1,6722e-007	0,26522
3,055	1,6798e-007	0,26643
3,075	1,6874e-007	0,26762
3,095	1,695e-007	0,26881

3,115	1,7024e-007	0,26999
3,135	1,7101e-007	0,27117
3,155	1,7176e-007	0,27233
3,175	1,7251e-007	0,27349
3,195	1,7327e-007	0,27464
3,215	1,7402e-007	0,27578
3,235	1,7477e-007	0,27692
3,255	1,7553e-007	0,27804
3,275	1,7629e-007	0,27916
3,295	1,7704e-007	0,28027
3,315	1,778e-007	0,28138
3,335	1,7856e-007	0,28247
3,355	1,7931e-007	0,28356
3,375	1,8007e-007	0,28464
3,395	1,8085e-007	0,28571
3,415	1,8162e-007	0,28677
3,435	1,8239e-007	0,28782
3,455	1,8317e-007	0,28887
3,475	1,8395e-007	0,28991
3,495	1,8473e-007	0,29093
3,515	1,8552e-007	0,29195
3,535	1,8632e-007	0,29296
3,555	1,8712e-007	0,29397
3,575	1,8792e-007	0,29496
3,595	1,8873e-007	0,29594
3,615	1,8956e-007	0,29692
3,635	1,9038e-007	0,29789
3,655	1,9122e-007	0,29884
3,675	1,9206e-007	0,29979
3,695	1,9291e-007	0,30073
3,715	1,9378e-007	0,30166
3,735	1,9465e-007	0,30258
3,755	1,9553e-007	0,30349
3,775	1,9643e-007	0,30439
3,795	1,9734e-007	0,30528
3,815	1,9826e-007	0,30616
3,835	1,9919e-007	0,30703
3,855	2,0014e-007	0,30789
3,875	2,0111e-007	0,30874
3,895	2,0209e-007	0,30958
3,915	2,0309e-007	0,31041
3,935	2,0415e-007	0,31125
3,955	2,0524e-007	0,31208
3,975	2,0636e-007	0,3129
3,9875	2,07e-007	0,3134
4,	2,077e-007	0,3139
4,01	2,0816e-007	0,31428
4,02	2,0881e-007	0,31467

4,035	2,0962e-007	0,31526
4,055	2,1076e-007	0,31602
4,075	2,1191e-007	0,31677
4,095	2,131e-007	0,31751
4,115	2,1431e-007	0,31824
4,135	2,1555e-007	0,31896
4,155	2,1683e-007	0,31966
4,175	2,1813e-007	0,32036
4,195	2,1948e-007	0,32104
4,215	2,2086e-007	0,32171
4,235	2,2228e-007	0,32237
4,255	2,2373e-007	0,32301
4,275	2,2524e-007	0,32364
4,295	2,2679e-007	0,32426
4,315	2,2838e-007	0,32486
4,335	2,3003e-007	0,32546
4,355	2,3173e-007	0,32603
4,375	2,3349e-007	0,32659
4,395	2,3531e-007	0,32714
4,415	2,372e-007	0,32767
4,435	2,3915e-007	0,32819
4,455	2,4117e-007	0,32869
4,475	2,4327e-007	0,32917
4,495	2,4545e-007	0,32964
4,515	2,4772e-007	0,33008
4,535	2,5009e-007	0,33051
4,555	2,5255e-007	0,33092
4,575	2,5512e-007	0,33131
4,595	2,5628e-007	0,33168
4,615	2,5485e-007	0,33236
4,635	2,5664e-007	0,33267
4,655	2,5626e-007	0,33298
4,675	2,5609e-007	0,33327
4,695	2,5598e-007	0,33352
4,715	2,5571e-007	0,33372
4,735	2,5541e-007	0,33389
4,755	2,5496e-007	0,33405
4,775	2,5475e-007	0,33418
4,795	2,5442e-007	0,33429
4,815	2,5403e-007	0,33436
4,835	2,5361e-007	0,33441
4,855	2,5316e-007	0,33442
4,875	2,5286e-007	0,33451
4,895	2,5242e-007	0,33459
4,915	2,5205e-007	0,33463
4,935	2,5168e-007	0,33464
4,955	2,513e-007	0,3346
4,975	2,5089e-007	0,33452

4,9875	2,5052e-007	0,33444
5,	2,4993e-007	0,33437
5,01	2,4886e-007	0,33434
5,02	2,4622e-007	0,33475
5,035	2,4784e-007	0,33441
5,055	2,4645e-007	0,33422
5,075	2,4458e-007	0,33399
5,095	2,4079e-007	0,33391
5,115	2,3696e-007	0,33378
5,135	2,3305e-007	0,33364
5,155	2,2903e-007	0,33348
5,175	2,246e-007	0,33339
5,195	2,1929e-007	0,33329
5,215	2,1427e-007	0,3332
5,235	2,092e-007	0,33309
5,255	2,0354e-007	0,33303
5,275	1,9715e-007	0,33301
5,295	1,911e-007	0,333
5,315	1,8494e-007	0,33299
5,335	1,7859e-007	0,33297
5,355	1,7217e-007	
5,375	1,6579e-007	
5,395	1,5938e-007	
5,415	1,5299e-007	
5,435	1,466e-007	
5,455	1,4022e-007	
5,475	1,3387e-007	
5,495	1,2754e-007	
5,515	1,2124e-007	
5,535	1,1498e-007	
5,555	1,0875e-007	
5,575	1,0258e-007	
5,595	9,6465e-008	
5,615	9,0427e-008	
5,635	8,4483e-008	
5,655	7,8655e-008	
5,675	7,2975e-008	
5,695	6,7479e-008	
5,715	6,2223e-008	
5,735	5,7273e-008	
5,755	5,2719e-008	
5,775	4,8677e-008	
5,795	4,5289e-008	
5,815	4,2715e-008	
5,835	4,1117e-008	
5,855	4,0616e-008	
5,875	4,1257e-008	
5,895	4,2995e-008	
5,915	4,5706e-008	

5,935	4,9232e-008	
5,955	5,3416e-008	
5,975	5,8119e-008	

5,9875	6,127e-008	
6,	6,4558e-008	

TABLE 20

Model (A4) > Static Structural (A5) > Solution (A6) > Probes

Object Name	*Force Reaction*	*Force Reaction 2*
State	Solved	
Definition		
Type	Force Reaction	
Location Method	Boundary Condition	
Boundary Condition	Displacement	Displacement 2
Orientation	Global Coordinate System	
Suppressed	No	
Options		
Result Selection	All	
Display Time	6, s	End Time
Results		
X Axis	542,84 N	-431,25 N
Y Axis	139,86 N	-139,86 N
Total	560,57 N	453,36 N
Maximum Value Over Time		
X Axis	542,92 N	3,0138e-007 N
Y Axis	284,54 N	1,3947e-007 N
Total	560,64 N	453,36 N
Minimum Value Over Time		
X Axis	0, N	-431,25 N
Y Axis	0, N	-284,54 N
Total	0, N	3,3209e-007 N
Information		
Time	6, s	
Load Step	6	
Substep	52	
Iteration Number	623	

FIGURE 7
Model (A4) > Static Structural (A5) > Solution (A6) > Force Reaction

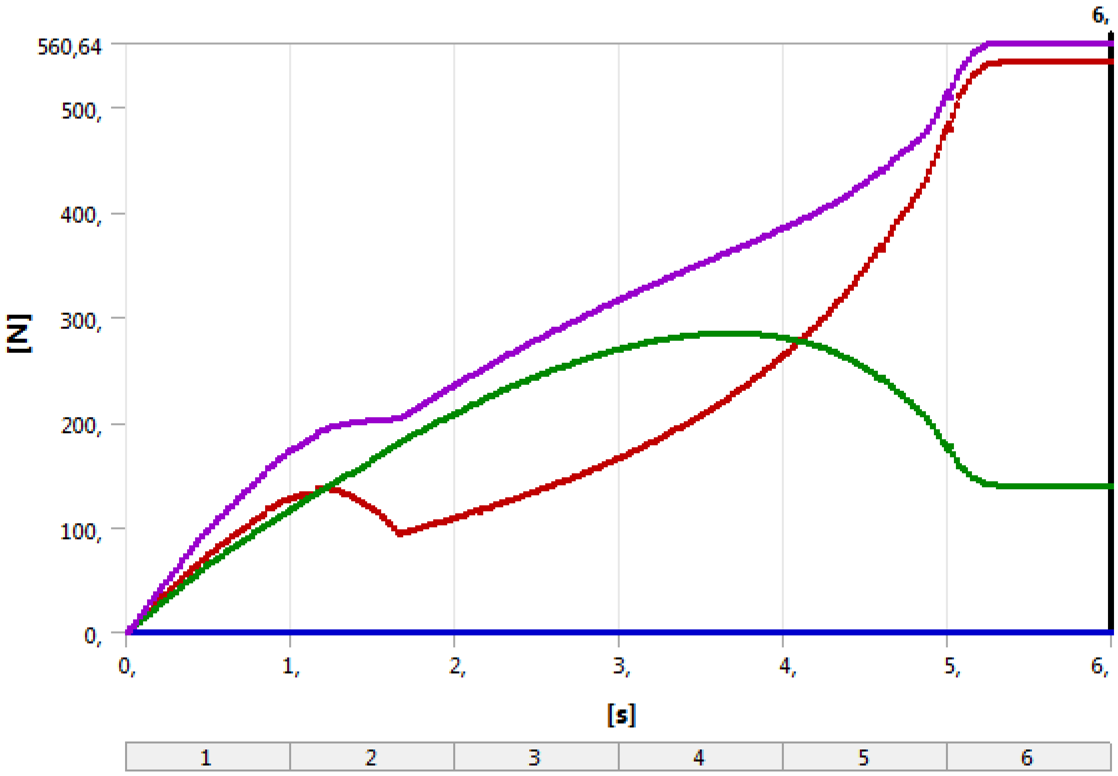

TABLE 21
Model (A4) > Static Structural (A5) > Solution (A6) > Force Reaction

Time [s]	Force Reaction (X) [N]	Force Reaction (Y) [N]	Force Reaction (Z) [N]	Force Reaction (Total) [N]
1,e-002	0,	0,	0,	0,
2,e-002	0,66587	0,94792		1,1584
3,e-002	1,9899	2,2909		3,0345
4,5e-002	4,2492	4,3569		6,0859
6,5e-002	7,5165	7,1341		10,363
8,5e-002	10,893	9,8897		14,713
0,105	14,316	12,619		19,084
0,125	17,748	15,319		23,445
0,145	21,121	17,986		27,742
0,165	24,308	20,613		31,871
0,185	27,291	23,198		35,819
0,205	30,503	25,867		39,994
0,225	33,508	28,518		44,001
0,245	36,562	31,142		48,027
0,265	39,709	33,745		52,111
0,285	42,754	36,312		56,093
0,305	45,715	38,846		59,99
0,325	48,626	41,349		63,83
0,345	52,32	44,735		68,837

0,365	54,988	47,161		72,442
0,385	57,754	49,568		76,108
0,405	60,486	51,946		79,73
0,425	63,145	54,296		83,279
0,445	65,76	56,619		86,776
0,465	68,924	59,757		91,222
0,485	71,318	62,015		94,51
0,505	73,968	64,281		97,997
0,525	76,795	66,589		101,64
0,545	79,102	68,865		104,88
0,565	81,297	71,101		108,
0,585	83,731	73,328		111,3
0,605	86,1	75,536		114,54
0,625	88,41	77,719		117,71
0,645	90,727	79,883		120,88
0,665	92,997	82,026		124,
0,685	95,24	84,149		127,09
0,705	97,46	86,251		130,15
0,725	99,651	88,334		133,17
0,745	101,82	90,397		136,16
0,765	103,94	92,446		139,1
0,785	106,	94,57		142,06
0,805	107,91	96,664		144,87
0,825	109,98	98,739		147,8
0,845	112,1	100,8		150,76
0,865	117,75	103,28		156,62
0,885	118,28	105,29		158,36
0,905	120,08	107,28		161,02
0,925	121,87	109,26		163,67
0,945	123,51	111,23		166,21
0,965	125,	113,17		168,62
0,985	126,36	115,11		170,93
1,	127,31	116,55		172,6
1,01	127,73	117,5		173,55
1,02	128,36	118,46		174,67
1,035	129,15	119,88		176,21
1,055	130,01	121,78		178,14
1,075	130,72	123,66		179,94
1,095	131,28	125,53		181,64
1,115	131,69	127,4		183,23
1,135	131,94	129,26		184,71
1,155	132,05	131,12		186,09
1,175	137,08	133,22		191,15
1,195	137,06	135,05		192,42
1,215	136,8	136,87		193,52
1,235	136,44	138,69		194,56
1,255	135,97	140,51		195,53
1,275	135,33	142,34		196,41

1,295	134,54	144,17		197,2
1,315	133,6	146,01		197,91
1,335	132,5	147,86		198,54
1,355	131,26	149,71		199,1
1,375	129,86	151,58		199,6
1,395	128,31	153,46		200,03
1,415	126,62	155,35		200,41
1,435	124,77	157,26		200,74
1,455	122,77	159,18		201,03
1,475	120,66	161,12		201,29
1,495	118,44	163,08		201,55
1,515	116,09	165,05		201,79
1,535	113,6	167,05		202,01
1,555	110,97	169,06		202,23
1,575	108,2	171,11		202,45
1,595	105,29	173,17		202,67
1,615	102,25	175,26		202,91
1,635	99,075	177,39		203,18
1,655	95,766	179,54		203,48
1,675	94,262	181,49		204,51
1,695	95,02	183,2		206,38
1,715	96,104	184,87		208,36
1,735	96,961	186,56		210,25
1,755	97,84	188,23		212,14
1,775	98,724	189,89		214,02
1,795	99,596	191,54		215,89
1,815	100,48	193,18		217,75
1,835	101,36	194,81		219,6
1,855	102,24	196,43		221,44
1,875	103,13	198,03		223,28
1,895	104,02	199,63		225,1
1,915	104,91	201,22		226,92
1,935	105,8	202,79		228,73
1,955	106,7	204,35		230,53
1,975	107,6	205,91		232,33
1,9875	108,22	206,87		233,47
2,	108,87	207,84		234,62
2,01	109,29	208,62		235,52
2,02	109,82	209,39		236,44
2,035	110,56	210,54		237,81
2,055	111,53	212,07		239,61
2,075	112,51	213,59		241,41
2,095	113,51	215,09		243,21
2,115	114,51	216,58		244,99
2,135	115,52	218,06		246,77
2,155	114,32	220,2		248,11
2,175	117,61	221,26		250,58
2,195	118,35	222,75		252,24

2,215	119,09	224,23		253,9
2,235	120,11	225,65		255,63
2,255	121,16	227,06		257,36
2,275	122,21	228,45		259,08
2,295	123,26	229,83		260,8
2,315	124,32	231,19		262,5
2,335	125,38	232,55		264,19
2,355	126,45	233,89		265,88
2,375	127,53	235,21		267,56
2,395	128,61	236,53		269,23
2,415	129,7	237,83		270,9

2,435	130,8	239,11		272,55
2,455	131,91	240,39		274,2
2,475	133,02	241,64		275,84
2,495	134,14	242,89		277,47
2,515	135,27	244,12		279,09
2,535	136,41	245,34		280,71
2,555	137,56	246,54		282,32
2,575	138,72	247,72		283,92
2,595	139,88	248,9		285,51
2,615	141,06	250,05		287,1
2,635	142,24	251,2		288,68
2,655	143,44	252,32		290,25
2,675	144,64	253,44		291,81
2,695	145,86	254,53		293,36
2,715	147,09	255,61		294,91
2,735	148,32	256,68		296,45
2,755	149,57	257,73		297,99
2,775	150,83	258,76		299,51
2,795	152,1	259,78		301,03
2,815	153,43	260,76		302,55
2,835	154,68	261,76		304,05
2,855	155,99	262,72		305,54
2,875	157,31	263,67		307,03
2,895	158,64	264,6		308,52
2,915	159,99	265,52		309,99
2,935	161,35	266,41		311,46
2,955	162,72	267,29		312,93
2,975	164,11	268,15		314,38
2,9875	165,01	268,67		315,3
3,	165,89	269,19		316,2
3,01	166,52	269,62		316,9
3,02	167,3	270,01		317,64
3,035	168,39	270,61		318,72
3,055	169,82	271,4		320,15
3,075	171,27	272,16		321,57
3,095	172,75	272,91		322,99
3,115	174,28	273,62		324,41

3,135	175,75	274,34		325,81
3,155	177,28	275,02		327,21
3,175	178,82	275,69		328,6
3,195	180,39	276,33		329,99
3,215	181,96	276,95		331,38
3,235	183,56	277,55		332,76
3,255	185,18	278,12		334,13
3,275	186,81	278,68		335,5
3,295	188,46	279,21		336,86
3,315	190,14	279,72		338,22
3,335	191,83	280,2		339,58
3,355	193,57	280,66		340,93
3,375	195,3	281,09		342,28
3,395	197,03	281,52		343,62
3,415	198,8	281,91		344,95
3,435	200,6	282,27		346,29
3,455	202,42	282,61		347,62
3,475	204,26	282,92		348,95
3,495	206,13	283,21		350,28
3,515	208,01	283,47		351,6
3,535	209,93	283,7		352,93
3,555	211,86	283,91		354,25
3,575	213,83	284,09		355,57
3,595	215,82	284,23		356,89
3,615	217,83	284,36		358,2
3,635	219,87	284,45		359,52
3,655	221,94	284,51		360,84
3,675	224,04	284,54		362,15
3,695	226,16			363,47
3,715	228,32	284,51		364,79
3,735	230,5	284,45		366,12
3,755	232,72	284,35		367,44
3,775	234,96	284,22		368,77
3,795	237,24	284,06		370,1
3,815	239,55	283,86		371,44
3,835	241,9	283,63		372,78
3,855	244,28	283,37		374,12
3,875	246,69	283,06		375,48
3,895	249,15	282,72		376,84
3,915	251,63	282,35		378,2
3,935	254,24	281,94		379,64
3,955	257,01	281,46		381,15
3,975	259,81	280,94		382,66
3,9875	261,51	280,6		383,57
4,	263,06	280,3		384,41
4,01	264,22	280,09		385,05
4,02	265,5	279,83		385,74
4,035	267,63	279,32		386,84

4,055	270,33	278,7		388,26
4,075	273,07	278,03		389,7
4,095	275,84	277,32		391,15
4,115	278,67	276,57		392,62
4,135	281,56	275,76		394,11
4,155	284,49	274,92		395,62
4,175	287,49	274,02		397,16
4,195	290,54	273,07		398,72
4,215	293,65	272,07		400,32
4,235	296,83	271,02		401,94
4,255	300,07	269,91		403,6
4,275	303,38	268,75		405,29
4,295	306,76	267,53		407,03
4,315	310,21	266,24		408,8
4,335	313,74	264,9		410,62
4,355	317,35	263,49		412,48
4,375	321,05	262,02		414,4
4,395	324,84	260,48		416,37
4,415	328,72	258,86		418,41
4,435	332,7	257,17		420,5
4,455	336,77	255,41		422,67
4,475	340,97	253,56		424,92
4,495	345,28	251,63		427,24
4,515	349,71	249,61		429,65
4,535	354,28	247,5		432,16
4,555	358,98	245,29		434,78
4,575	363,83	242,98		437,5
4,595	368,85	240,56		440,36
4,615	364,43	242,38		437,67
4,635	374,06	237,61		443,15
4,655	378,89	235,18		445,95
4,675	384,47	232,36		449,23
4,695	390,42	229,32		452,79
4,715	394,11	227,03		454,83
4,735	398,34	224,4		457,2
4,755	402,22	221,94		459,39
4,775	406,65	219,16		461,95
4,795	411,14	216,31		464,57
4,815	415,65	213,4		467,23
4,835	420,27	210,39		469,99
4,855	425,05	207,26		472,89
4,875	430,87	203,87		476,67
4,895	438,05	199,87		481,49
4,915	445,45	195,72		486,55
4,935	453,23	191,36		491,97
4,955	461,56	186,67		497,88
4,975	470,44	181,68		504,31
4,9875	475,97	178,57		508,36

5,	481,13	175,64		512,19
5,01	483,64	174,16		514,05
5,02	478,07	176,84		509,73
5,035	492,7	168,87		520,84
5,055	501,39	164,01		527,53
5,075	510,67	158,86		534,81
5,095	514,35	156,67		537,68
5,115	519,22	153,89		541,54
5,135	524,64	150,88		545,91
5,155	530,28	147,77		550,48
5,175	532,65	146,22		552,35
5,195	534,73	144,83		553,99
5,215	537,06	143,39		555,88
5,235	540,23	141,57		558,47
5,255	541,74	140,66		559,71
5,275	541,98	140,42		559,88
5,295	542,05	140,32		559,92
5,315	542,35	140,13		560,16
5,335	542,77	139,89		560,51
5,355	542,92	139,81		560,64
5,375	542,83	139,86		560,56
5,395	542,84			560,57
5,415	542,85			

5,435	542,84			
5,455				
5,475				
5,495				
5,515				
5,535				
5,555				
5,575				
5,595				
5,615				
5,635				
5,655				
5,675				
5,695				
5,715				
5,735				
5,755				
5,775				
5,795				
5,815				
5,835				
5,855				
5,875				
5,895				

5,915				
5,935				
5,955				
5,975				
5,9875				
6,				

FIGURE 8
Model (A4) > Static Structural (A5) > Solution (A6) > Force Reaction 2

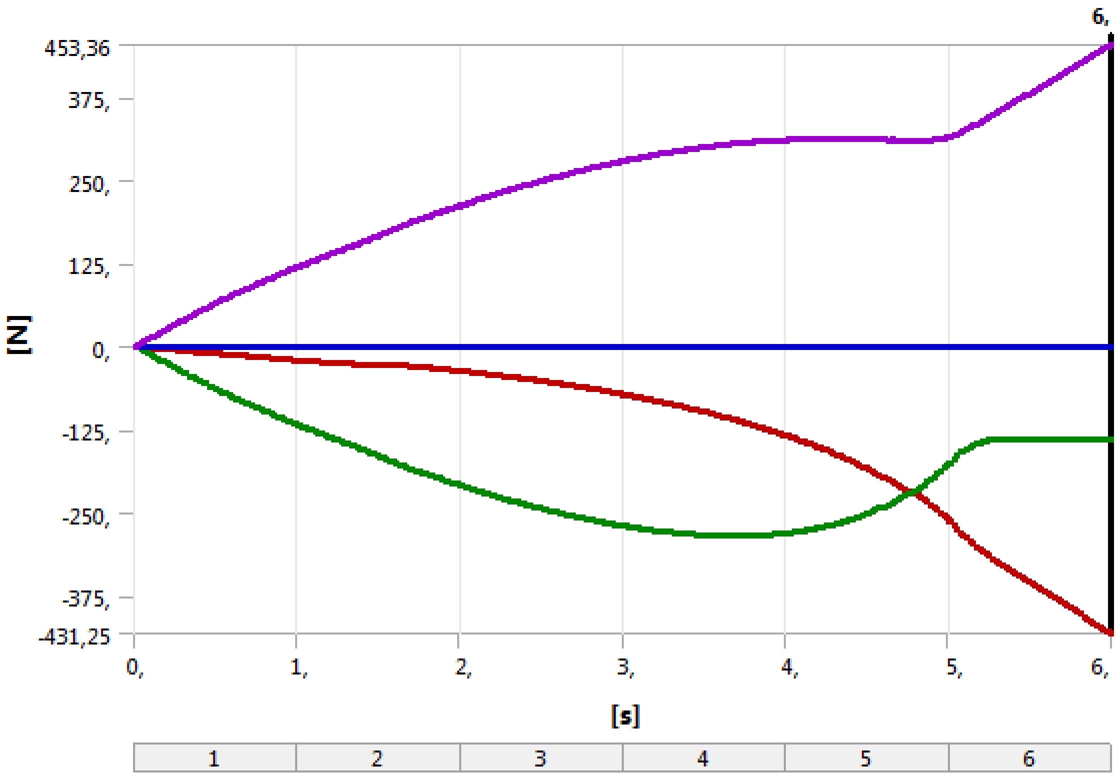

TABLE 22
Model (A4) > Static Structural (A5) > Solution (A6) > Force Reaction 2

Time [s]	Force Reaction 2 (X) [N]	Force Reaction 2 (Y) [N]	Force Reaction 2 (Z) [N]	Force Reaction 2 (Total) [N]
1,e-002	3,0138e-007	1,3947e-007	0,	3,3209e-007
2,e-002	-0,14314	-0,94792		0,95866
3,e-002	-0,36878	-2,2909		2,3203
4,5e-002	-0,71701	-4,3569		4,4155
6,5e-002	-1,1899	-7,1341		7,2327
8,5e-002	-1,6653	-9,8898		10,029
0,105	-2,1407	-12,619		12,799
0,125	-2,614	-15,319		15,541
0,145	-3,0791	-17,986		18,248
0,165	-3,5301	-20,613		20,913

0,185	-3,9642	-23,198		23,535
0,205	-4,4455	-25,867		26,246
0,225	-4,9169	-28,518		28,938
0,245	-5,3843	-31,142		31,604
0,265	-5,8578	-33,745		34,249
0,285	-6,3232	-36,312		36,858
0,305	-6,7776	-38,846		39,433
0,325	-7,2254	-41,349		41,976
0,345	-7,7506	-44,735		45,401
0,365	-8,1658	-47,161		47,863
0,385	-8,5902	-49,568		50,307
0,405	-9,0129	-51,946		52,722
0,425	-9,4261	-54,296		55,108
0,445	-9,8341	-56,619		57,467
0,465	-10,271	-59,757		60,634
0,485	-10,65	-62,015		62,923
0,505	-11,053	-64,281		65,225
0,525	-11,474	-66,589		67,57
0,545	-11,852	-68,865		69,877
0,565	-12,208	-71,101		72,142
0,585	-12,591	-73,328		74,401
0,605	-12,97	-75,536		76,642
0,625	-13,342	-77,719		78,856
0,645	-13,715	-79,883		81,052
0,665	-14,085	-82,026		83,227
0,685	-14,452	-84,149		85,381
0,705	-14,819	-86,252		87,515
0,725	-15,183	-88,334		89,629
0,745	-15,546	-90,397		91,724
0,765	-15,912	-92,446		93,806
0,785	-16,341	-94,57		95,971
0,805	-16,754	-96,663		98,104
0,825	-17,184	-98,739		100,22
0,845	-17,623	-100,8		102,33
0,865	-18,371	-103,28		104,9
0,885	-18,665	-105,29		106,93
0,905	-19,099	-107,28		108,97
0,925	-19,515	-109,26		110,99
0,945	-19,921	-111,23		113,
0,965	-20,317	-113,17		114,98
0,985	-20,709	-115,11		116,96
1,	-20,997	-116,55		118,43
1,01	-21,182	-117,5		119,4
1,02	-21,37	-118,46		120,37
1,035	-21,649	-119,88		121,82
1,055	-22,011	-121,78		123,75
1,075	-22,364	-123,66		125,66
1,095	-22,708	-125,53		127,57

1,115	-23,044	-127,4		129,47
1,135	-23,372	-129,26		131,36
1,155	-23,691	-131,12		133,25
1,175	-24,396	-133,22		135,44
1,195	-24,661	-135,05		137,28
1,215	-24,947	-136,87		139,13
1,235	-25,216	-138,69		140,97
1,255	-25,476	-140,51		142,8
1,275	-25,727	-142,34		144,65
1,295	-25,97	-144,17		146,49
1,315	-26,204	-146,01		148,34
1,335	-26,43	-147,86		150,2
1,355	-26,647	-149,71		152,07
1,375	-26,856	-151,58		153,94
1,395	-27,057	-153,46		155,82
1,415	-27,25	-155,35		157,72
1,435	-27,435	-157,26		159,63
1,455	-27,613	-159,18		161,56
1,475	-27,785	-161,12		163,5
1,495	-27,954	-163,08		165,46
1,515	-28,116	-165,05		167,43
1,535	-28,272	-167,05		169,42
1,555	-28,421	-169,06		171,44
1,575	-28,563	-171,11		173,47
1,595	-28,7	-173,17		175,53
1,615	-28,83	-175,27		177,62
1,635	-28,955	-177,39		179,73
1,655	-29,073	-179,54		181,87
1,675	-29,328	-181,49		183,85
1,695	-29,751	-183,2		185,6
1,715	-30,194	-184,87		187,32
1,735	-30,644	-186,56		189,06
1,755	-31,09	-188,23		190,78
1,775	-31,539	-189,89		192,49
1,795	-31,992	-191,54		194,19
1,815	-32,449	-193,18		195,89
1,835	-32,912	-194,81		197,57
1,855	-33,378	-196,43		199,24
1,875	-33,85	-198,03		200,9
1,895	-34,326	-199,63		202,56
1,915	-34,807	-201,22		204,2
1,935	-35,293	-202,79		205,84
1,955	-35,784	-204,35		207,46
1,975	-36,28	-205,91		209,08
1,9875	-36,599	-206,87		210,08
2,	-36,934	-207,84		211,09
2,01	-37,2	-208,62		211,92
2,02	-37,472	-209,39		212,72

2,035	-37,881	-210,54		213,92
2,055	-38,428	-212,07		215,53
2,075	-38,98	-213,59		217,12
2,095	-39,538	-215,09		218,7
2,115	-40,102	-216,58		220,26
2,135	-40,671	-218,06		221,82
2,155	-40,897	-220,2		223,97
2,175	-41,677	-221,26		225,15
2,195	-42,236	-222,75		226,72
2,215	-42,813	-224,23		228,28
2,235	-43,411	-225,65		229,79
2,255	-44,017	-227,06		231,28
2,275	-44,629	-228,45		232,77
2,295	-45,246	-229,83		234,24
2,315	-45,87	-231,19		235,7
2,335	-46,5	-232,55		237,15
2,355	-47,136	-233,89		238,59
2,375	-47,779	-235,21		240,02
2,395	-48,428	-236,53		241,43
2,415	-49,084	-237,83		242,84

2,435	-49,747	-239,11		244,23
2,455	-50,417	-240,39		245,62
2,475	-51,093	-241,64		246,99
2,495	-51,777	-242,89		248,35
2,515	-52,468	-244,12		249,69
2,535	-53,166	-245,34		251,03
2,555	-53,871	-246,54		252,35
2,575	-54,584	-247,72		253,67
2,595	-55,305	-248,9		254,97
2,615	-56,033	-250,05		256,26
2,635	-56,769	-251,2		257,53
2,655	-57,513	-252,32		258,8
2,675	-58,264	-253,44		260,05
2,695	-59,024	-254,53		261,29
2,715	-59,792	-255,61		262,51
2,735	-60,568	-256,68		263,73
2,755	-61,353	-257,73		264,93
2,775	-62,146	-258,76		266,12
2,795	-62,948	-259,78		267,29
2,815	-63,758	-260,76		268,44
2,835	-64,578	-261,76		269,61
2,855	-65,406	-262,72		270,74
2,875	-66,243	-263,67		271,87
2,895	-67,09	-264,6		272,98
2,915	-67,946	-265,52		274,07
2,935	-68,811	-266,41		275,16
2,955	-69,686	-267,29		276,23
2,975	-70,57	-268,15		277,28

2,9875	-71,128	-268,67		277,93
3,	-71,69	-269,19		278,57
3,01	-72,12	-269,63		279,1
3,02	-72,594	-270,01		279,6
3,035	-73,285	-270,61		280,35
3,055	-74,208	-271,4		281,36
3,075	-75,142	-272,16		282,35
3,095	-76,088	-272,91		283,32
3,115	-77,042	-273,62		284,26
3,135	-78,011	-274,34		285,21
3,155	-78,988	-275,02		286,14
3,175	-79,976	-275,68		287,05
3,195	-80,977	-276,33		287,95
3,215	-81,988	-276,95		288,83
3,235	-83,011	-277,55		289,69
3,255	-84,045	-278,12		290,54
3,275	-85,091	-278,68		291,38
3,295	-86,15	-279,21		292,2
3,315	-87,22	-279,72		293,
3,335	-88,303	-280,2		293,79
3,355	-89,396	-280,66		294,55
3,375	-90,505	-281,09		295,31
3,395	-91,629	-281,52		296,05
3,415	-92,763	-281,91		296,78
3,435	-93,91	-282,27		297,48
3,455	-95,072	-282,61		298,17
3,475	-96,247	-282,92		298,85
3,495	-97,436	-283,21		299,5
3,515	-98,639	-283,47		300,14
3,535	-99,856	-283,7		300,76
3,555	-101,09	-283,91		301,37
3,575	-102,34	-284,09		301,96
3,595	-103,59	-284,23		302,52
3,615	-104,88	-284,36		303,08
3,635	-106,17	-284,45		303,62
3,655	-107,48	-284,51		304,13
3,675	-108,8	-284,54		304,63
3,695	-110,15			305,12
3,715	-111,51	-284,51		305,58
3,735	-112,88	-284,45		306,03
3,755	-114,28	-284,35		306,46
3,775	-115,69	-284,22		306,87
3,795	-117,12	-284,06		307,26
3,815	-118,57	-283,86		307,63
3,835	-120,04	-283,63		307,99
3,855	-121,52	-283,37		308,32
3,875	-123,03	-283,06		308,64
3,895	-124,56	-282,72		308,94

3,915	-126,1	-282,34		309,23
3,935	-127,72	-281,94		309,52
3,955	-129,4	-281,46		309,78
3,975	-131,1	-280,94		310,03
3,9875	-132,11	-280,6		310,15
4,	-133,12	-280,3		310,31
4,01	-133,82	-280,09		310,42
4,02	-134,71	-279,83		310,56
4,035	-135,97	-279,32		310,66
4,055	-137,65	-278,69		310,84
4,075	-139,35	-278,02		310,99
4,095	-141,06	-277,32		311,13
4,115	-142,81	-276,56		311,26
4,135	-144,59	-275,76		311,37
4,155	-146,39	-274,92		311,46
4,175	-148,22	-274,02		311,54
4,195	-150,09	-273,07		311,6
4,215	-151,99	-272,07		311,64
4,235	-153,92	-271,02		311,67
4,255	-155,88	-269,91		311,69
4,275	-157,88	-268,75		
4,295	-159,92	-267,52		311,68
4,315	-161,99	-266,24		311,65
4,335	-164,11	-264,9		311,61
4,355	-166,27	-263,49		311,56
4,375	-168,47	-262,02		311,5
4,395	-170,72	-260,47		311,43
4,415	-173,01	-258,86		311,35
4,435	-175,36	-257,17		311,27
4,455	-177,76	-255,41		311,18
4,475	-180,21	-253,56		311,08
4,495	-182,73	-251,63		310,98
4,515	-185,3	-249,61		310,87
4,535	-187,95	-247,5		310,77
4,555	-190,66	-245,29		310,67
4,575	-193,45	-242,98		310,58
4,595	-196,32	-240,56		310,5
4,615	-195,53	-242,39		311,42
4,635	-199,74	-237,61		310,41
4,655	-202,67	-235,18		310,46
4,675	-205,84	-232,36		310,42
4,695	-209,16	-229,32		310,38
4,715	-211,41	-227,03		310,22
4,735	-213,96	-224,4		310,05
4,755	-216,4	-221,94		309,98
4,775	-218,97	-219,16		309,81
4,795	-221,62	-216,31		309,68
4,815	-224,3	-213,4		309,59

4,835	-227,03	-210,39		309,53
4,855	-229,84	-207,25		309,49
4,875	-233,15	-203,88		309,72
4,895	-237,22	-199,86		310,19
4,915	-241,34	-195,72		310,73
4,935	-245,65	-191,35		311,38
4,955	-250,23	-186,67		312,19
4,975	-255,08	-181,68		313,17
4,9875	-258,15	-178,57		313,89
5,	-261,14	-175,64		314,71
5,01	-262,99	-174,16		315,43
5,02	-261,77	-176,84		315,91
5,035	-268,48	-168,86		317,17
5,055	-273,65	-164,01		319,04
5,075	-279,37	-158,86		321,38
5,095	-283,14	-156,67		323,6
5,115	-287,54	-153,89		326,13
5,135	-292,25	-150,88		328,9
5,155	-297,11	-147,77		331,83
5,175	-300,49	-146,22		334,17
5,195	-304,16	-144,83		336,88
5,215	-307,8	-143,39		339,56
5,235	-311,88	-141,57		342,51
5,255	-315,39	-140,66		345,34
5,275	-318,63	-140,42		348,2
5,295	-321,58	-140,32		350,86
5,315	-324,71	-140,13		353,66
5,335	-328,	-139,89		356,59
5,355	-331,19	-139,81		359,49
5,375	-334,24	-139,86		362,32
5,395	-337,35			365,19
5,415	-340,46			368,07

5,435	-343,58			370,95
5,455	-346,69			373,84
5,475	-349,8			376,73
5,495	-352,92			379,62
5,515	-356,03			382,51
5,535	-359,14			385,41
5,555	-362,25			388,31
5,575	-365,36			391,21
5,595	-368,47			394,12
5,615	-371,58			397,03
5,635	-374,68			399,94
5,655	-377,79			402,85
5,675	-380,9			405,76
5,695	-384,			408,68
5,715	-387,11			411,6

5,735	-390,21			414,52
5,755	-393,31			417,44
5,775	-396,42			420,37
5,795	-399,52			423,29
5,815	-402,62			426,22
5,835	-405,72			429,15
5,855	-408,82			432,08
5,875	-411,91			435,01
5,895	-415,01			437,94
5,915	-418,11			440,88
5,935	-421,2			443,81
5,955	-424,29			446,75
5,975	-427,38			449,69
5,9875	-429,32			451,52
6,	-431,25			453,36

Material Data

Structural Steel

TABLE 23
Structural Steel > Constants

Density	7850, kg m^-3
Coefficient of Thermal Expansion	1,2e-005 C^-1
Specific Heat	434, J kg^-1 C^-1
Thermal Conductivity	60,5 W m^-1 C^-1
Resistivity	1,7e-007 ohm m

TABLE 24

Structural Steel > Compressive Ultimate Strength

Compressive Ultimate Strength Pa
0,

TABLE 25

Structural Steel > Compressive Yield Strength

Compressive Yield Strength Pa
2,5e+008

TABLE 26

Structural Steel > Tensile Yield Strength

Tensile Yield Strength Pa
2,5e+008

TABLE 27

Structural Steel > Tensile Ultimate Strength

Tensile Ultimate Strength Pa
4,6e+008

TABLE 28

Structural Steel > Isotropic Secant Coefficient of Thermal Expansion
Reference Temperature C
22,

TABLE 29
Structural Steel > Alternating Stress Mean Stress

Alternating Stress Pa	Cycles	Mean Stress Pa
3,999e+009	10,	0,
2,827e+009	20,	0,
1,896e+009	50,	0,
1,413e+009	100,	0,
1,069e+009	200,	0,
4,41e+008	2000,	0,
2,62e+008	10000	0,
2,14e+008	20000	0,
1,38e+008	1,e+005	0,
1,14e+008	2,e+005	0,
8,62e+007	1,e+006	0,

TABLE 30
Structural Steel > Strain-Life Parameters

Strength Coefficient Pa	Strength Exponent	Ductility Coefficient	Ductility Exponent	Cyclic Strength Coefficient Pa	Cyclic Strain Hardening Exponent
9,2e+008	-0,106	0,213	-0,47	1,e+009	0,2

TABLE 31
Structural Steel > Isotropic Elasticity

Temperature C	Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa
	2,e+011	0,3	1,6667e+011	7,6923e+010

TABLE 32

Structural Steel > Isotropic Relative Permeability
Relative Permeability
1000

PU_STRESS-STRAIN

TABLE 33
PU_STRESS-STRAIN > Uniaxial Test Data

Strain m m^-1	Stress Pa	Temperature C
0,	-67727	

1,192e-002	92424	

3,9115e-002	-31212	
6,4523e-002	30758	
8,9781e-002	59545	
0,11503	90606	
0,14029	1,1712e+005	
0,16554	1,4364e+005	
0,19079	1,8712e+005	
0,21604	2,1303e+005	
0,2413	2,5303e+005	
0,26655	2,847e+005	
0,2918	3,1773e+005	
0,31705	3,4394e+005	
0,34231	3,7773e+005	
0,36756	4,0515e+005	
0,39281	4,347e+005	
0,41806	4,6379e+005	
0,44332	4,9455e+005	
0,46857	5,2606e+005	
0,49382	5,4758e+005	
0,51908	5,7045e+005	
0,54433	5,8833e+005	
0,56958	6,2485e+005	
0,59483	6,4227e+005	
0,62008	6,6697e+005	
0,64534	6,9242e+005	
0,67059	7,1455e+005	
0,69584	7,3667e+005	
0,7211	7,6455e+005	
0,74635	7,9212e+005	
0,7716	8,1773e+005	
0,79685	8,3864e+005	
0,8221	8,6076e+005	
0,84736	8,8318e+005	
0,87261	9,1303e+005	
0,89786	9,3424e+005	
0,92311	9,4894e+005	
0,94837	9,8348e+005	
0,97362	1,0088e+006	
0,99887	1,0273e+006	
1,0241	1,0503e+006	
1,0494	1,0715e+006	
1,0746	1,0929e+006	
1,0999	1,1262e+006	
1,1251	1,1327e+006	
1,1504	1,1665e+006	
1,1756	1,1832e+006	
1,2009	1,2171e+006	

1,2261	1,2314e+006	
1,2514	1,2573e+006	
1,2767	1,2798e+006	
1,3019	1,3056e+006	
1,3272	1,3274e+006	
1,3524	1,3476e+006	
1,3777	1,3721e+006	
1,4029	1,4014e+006	
1,4282	1,4238e+006	
1,4534	1,4456e+006	
1,4787	1,4717e+006	
1,5039	1,4891e+006	
1,5292	1,5073e+006	
1,5544	1,538e+006	
1,5797	1,5568e+006	
1,6049	1,5782e+006	
1,6302	1,6091e+006	
1,6554	1,637e+006	
1,6807	1,6571e+006	
1,7059	1,6803e+006	
1,7312	1,6994e+006	
1,7564	1,7259e+006	
1,7817	1,7489e+006	
1,807	1,778e+006	
1,8322	1,7945e+006	
1,8575	1,8156e+006	
1,8827	1,8365e+006	
1,908	1,8558e+006	
1,9332	1,8806e+006	
1,9585	1,8982e+006	
1,9837	1,9208e+006	
2,009	1,9321e+006	
2,0342	1,9436e+006	
2,0595	1,9517e+006	
2,0847	1,9727e+006	
2,11	1,975e+006	

TABLE 34
PU_STRESS-STRAIN > Isotropic Elasticity

Temperature C	Young's Modulus Pa	Poisson's Ratio	Bulk Modulus Pa	Shear Modulus Pa
	6,157e+006	0,47	3,4206e+007	2,0942e+006

Appendix 7 Test procedure

A		Issued for IDC					
Rev.	Date	Description	Prepared by	Discipline check	Discipline approval	Contractor approval	Client Acceptance

DFO / Norsok Code: KA	Area Code:	Key words (description): NA
WBS Code: NA	System Code:	For Contractor use: NA

Code 1
Accepted

Code 2
Accepted with comments incorporated

Code 3
Not Accepted, revise and resubmit

Code 4
Accepted, for information only

Code 5
Interface information
As clouded is accepted and frozen

Responsible unit: NA

Supplier reference: NA

Procurement reference:

Tag. no. / Line no.

File code:	Pages:	Volume:	Enclosed
NA	27	NA	NA

Document title:

Test Procedure

Contractor Name:

IK-Group

Contract / Supplier Project no.:

20825

Project name:

Polyurethane sealing discs on cleaning pigs; characterization and dynamic behavior

Document Number:				Revision:
Supplier Document Number:				
20856-IK-Z-KA-0001				
Project Code	Originator Code	Discipline Code	Document Type Code	Sequence No.

Package/ Project Title:	Polyurethane sealing discs on cleaning pigs; characterization and dynamic behavior	
Document Title:	Test Procedure	
IK Document No:	20825-IK-Z-KA-0001	

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Revision Log

Rev.	*Date*	*Section(s)*	*Page(s)*	*Reason*
A		ALL	ALL	IDC

Package/ Project Title:	Polyurethane sealing discs on cleaning pigs; characterization and dynamic behavior
Document Title:	Test Procedure
IK Document No:	20825-IK-Z-KA-0001

1 General

1.1 Introduction

This document describes the test setup and all related equipment, steps etc. to do a verification test on the PU model, which is covered in the master thesis topic; Polyurethane sealing discs on cleaning pigs; characterization and dynamic behaviour.

For Pigs the friction is almost directly connected to the stiffness of the PU components, there are small variables from added stiffness due to pigging pressure (this can almost be neglected) and change in stiffness when passing features. For these tests, there are no features in the system making the stiffness the dominating variable for both static and dynamical friction.

Variables are Bypass in the seals, if the pressure/flow varies the predominate reasons would be

- Unstable PIG (large vertical/sideways movement) (large bypass)
- Force in the system is to low, resulting in speed variation (force near friction total force)
- Variable flow from water main
- Other?

1.2 Purpose and Scope of the Document

To verify the Finite element analysis tests will be executed on a 12 m test rig. These tests are to verify the time of travel as shown in document; Polyurethane sealing discs on cleaning pigs; characterization and dynamic behavior. Pressure, flow and time will be logged using a computer and the data will need to be analyzed to determine when the PIG flips and starts flowing.

The tests will be executed according to this procedure at IK`s Facilities in Forus.

1.3 Executive Summary

The purpose of the Test is to prove the following

- Verify that the finite element model shows the correct wall force and that time of travel can be estimated using the model
- Verify total amount of bypass, if possible

1.4 Reference Documents

The following table lists the reference documents.

Table 1 - Reference Documents

Pos.	Document nr.	Description
1		**QA Plan**
2		**HSE Plan**
3		**GA Pig**
4		**GA Test Jig**

1.5 ABBREVIATIONS

The following table lists abbreviations used through this document.

Table 2 - Abbreviations

Abbreviation	Description
IK	IK-Norway AS
PPE	Personnel Protective Equipment
SJA	Safe Job Analysis
GA	General Arrangement
SOW	Scope of Work
PCV	Pressure Control Valve
HSE	Health, Safety and Environment
QA	Quality Assurance

1.6 SYMBOLS

The following symbols found throughout this manual, highlights special messages to alert the operator to specific information concerning PERSONNEL, EQUIPMENT, PROCESS or the ENVIRONMENTAL IMPACT.

Table 3 - Symbols

Symbol	Description
	WARNING: Failure to follow these directions in this WARNING can result in bodily harm and hazard, resulting in harm or loss of life, and/or extensive damage to equipment.
	CAUTION: Failure to follow these directions can result in damage to equipment.
	CAUTION: Failure to follow these directions can result in environmental hazard
	NOTE: This is for information or specific instructions

2 HSE/QA

2.1 SAFETY

Safety of personnel, equipment and the environment are paramount prior to and during all phases of the project.

Work shall not be started unless it can be completely safe. Work shall be stopped if an unsafe situation arises until such time as it can safely be resolved.

SJA in chapter "0" shall be conducted prior to testing with participation of all key personnel and operators. The site shall be free of all hazards prior to starting operations including, but not limited to:

- Electrical
- Mechanical
- Fire
- Differential pressure
- Chemical
- Noise
- Crushing
- Improper lifting

The FAT Responsible is responsible to see that proper protective measures, such as electrical isolations, access barriers and warning signs are in place, and will ensure that all personnel are suitably dressed with personal protective equipment.

The FAT Responsible is responsible for holding a safety briefing prior to work, to familiarize all involved personnel, with any hazardous or potentially hazardous aspects of the work.

The FAT Responsible is responsible for keeping all personnel in the general area advised as to when the work will start and finish.

All personnel participating in the test shall be familiarized with the relevant material/Chemical. The operators are responsible for studying the relevant material/Chemical and FAT Responsible is responsible for ensuring that all necessary actions are taken.

All non-conformance reports shall be addressed and completed prior to final sign-off of the procedure.

Requirements for personal protective equipment will vary with the type of work task that is done. Protective boots, gloves, coverall, helmet and protective glasses shall always be used. Additional requirements will be stated in the SJA included in this document and the findings shall be implemented in the procedure prior to conducting the FAT.

2.2 PRE JOB ACTIVITIES & FAMILIARIZATION

To ensure that the FAT is ready to start the following table shall be filled out.

Table 4 - Pre Job Activities & Familiarization

Pos.	Description	Date	Sign. Responsible
1	Ensure all participants know where to find first aid stations if needed.		
2	Has SJA been conducted?		
3	Ensure all participants are familiar where to find emergency exits and emergency routines.		
4	Has all the necessary equipment arrived and is it intact?		
5	Has all the necessary project personnel arrived?		
6	Water available and connected to the test RIG via 2" hose?		
7	All lifting equipment to be inspected and certified to the required lifting capacity (IF APPLICABLE).		
8	Has tool box talk been conducted?		
9	Has safety barrier been established?		
10	Have all pressure hoses been checked and confirmed in working order?		
11	Has all logging equipment been calibrated and installed on the rig?		

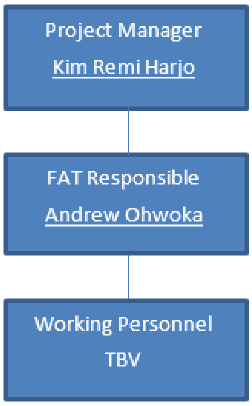
2.3 FAT ORGANIZATION CHART

Mention the names of the participants in the FAT.

Include the client representative if it is defined.

If it is not possible, fill the names in the SJA names list.

If someone comes after to participate in the FAT, needs to go through the SJA before participate and add the name there.



3 PRODUCT OVERVIEW

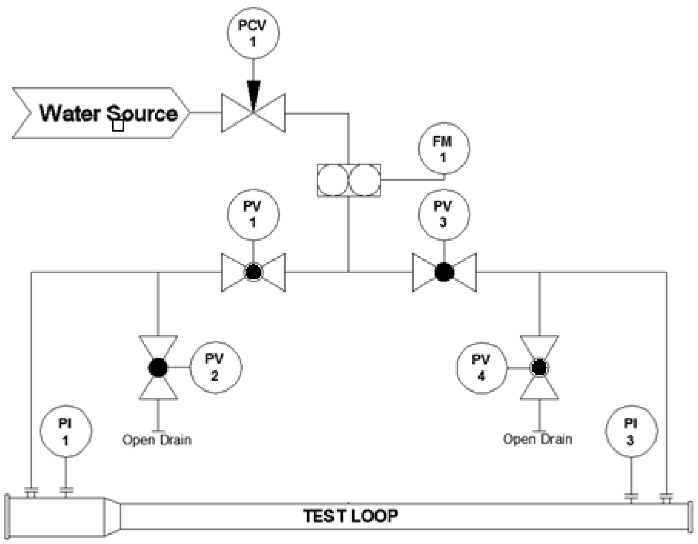
3.1 BI-DI PIG

The Bi Di pig consists of two sets of seal discs and brushes. One set is designed to seal and clean in the 10" section while the other is designed to seal and clean in the 8" section. The 10" guides are slotted to allow them to bend more easily, this enables it to traverse the 8" section without being strained too much. The pig is designed as a Bi Di pig to enable it to travel in both directions.

3.2 THE TEST RIG GA

The test rig has been designed to simulate a straight PIG run and consist of 11m section, 2 x pressure transmitters and 1 flow transmitter.

The test loop will be operated by the PCV and a manifold consisting of 4 valves (PV1-4). This will allow the operators to reverse the flow from the manifold.



3.3 BLIND FLANGES

The blind flanges have been designed with pig stoppers to make sure that the pig stops in the right location. This will ensure that that the 2" kicker line always are behind the pig and can be used to drive the pig through the pipe.

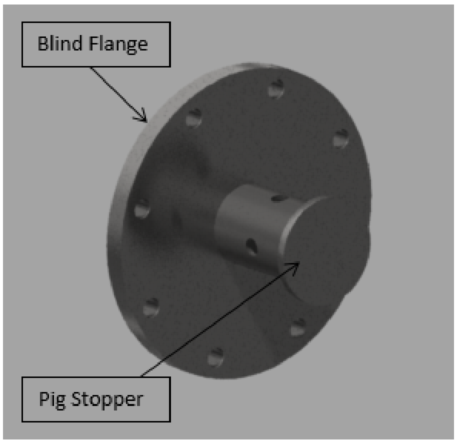


Figure 4 - End Flange with pig stopper

4 FAT PROCEDURE

NOTE: This part of the procedure may be repeated for separate tests to be performed on different equipment.

4.1 SCOPE AND ACCEPTANCE CRITERIA OF THE TEST

The scope and acceptance criteria for subject tests are in accordance with the following:

Table 5 - Scope and Main Acceptance Criteria of the Test

Pos.	Scope	Acceptance Criteria
1		
2		
3		

4.2 TEST AND TESTED EQUIPMENT

To perform this FAT the below listed equipment/parts are required.

Table 6 - Test and Tested Equipment

Pos.	Qty.	Description	Comments
1	1	Test Rig	
2	1	BiDi Pig	
3	2	Pressure Transmitters	
4	2	Hoses to accommodate 3" water main to manifold	
5	2	Lifting Straps according to slinged load	
6	1	Crane/lifting capacity min 1T and 6m high	
7	1	Manifold to control the flow direction	
8	1	Pressure control valve	
9	1	Flow transmitter	
10	1	Computer with software	
11	1	Chain Talley	
12	1	Timer	

4.3 PRE-TEST CHECK

Before the FAT test can commence, the test rig must be assembled. The surrounding area should be cleared and free of operations that could conflict with the test. All participants must wear the appropriate PPE equipment and the area must be enclosed by necessary barriers. The system will be tested to 7,2 Barg and the pressure variations in water main is lower (measured between 6.8 to 7.2 Barg), hence as PSV has not been included for the test with water main.

Table 7 - Pre-Test Check Steps

Step	Description/Pictures	Acceptance Criteria if Applicable	Comments/ Signature
1	Are Necessary PPE being used	Visual	
2	All equipment in the check list is present	Visual	
3	Check all seals/gaskets and torque bolts	Visual	
4	Close valves PV1, PV 2, PV 3 and PV 4	Mechanically closed	
5	Make sure that the required hoses are present and connected (rated at 30 bar)	Visual	
6	Check access to water source	Visual	
7	Make sure the pressure gauges are installed correctly	Visual	
8	Make sure that the pressure gauges has been calibrated	Visual	
9	Has the rig been filled with water?	Visual	
10	Erect safety barriers around the test rig	Visual	
11	Pressure test system to 15 bar	Visual	
12	Check for leaks	Visual	

IK Representative	Client Representative
Date: Signature:	Date: Signature:

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Step	Description/Pictures	Acceptance Criteria if Applicable/Values Obtained	Comments/ Signature
16	Pre-set the reverse flow in the manifold by opening PV3	Visual	
17	Start flipping the disc on the pig by opening the outlet in the launcher (PV2)	Visual	
18	Log pressure at all two locations PI 1: _______Bar PI 3: _______Bar	Gauged/Written	
19	A pop and time depended pressure drop	Audio/ Gauged	Sudden pressure drop
	Record the pressure needed to flip the discs in the 8" line. Flipping Pressure_________bar	Gauged/ Written	
20	Keep pumping until the pig has returned to the other side	Audible	
21	Launch PIG by opening the drain valve PV 4 Note! Start Timer and listen for the PIG at the end stopper.	Visual flow	
22	Log pressure at all three locations PI 1: _______Bar FM 1: _______L/min PI 3: _______Bar	Logged	
23	Close the 2" valves (PV2 and PV3)	Visual	
24	Bleed of pressure	Visual	
25	Remove Blind Flange and verify that the pig is in the major barrel	Visual	
26	Remove the pig and inspect for damage The Pig shall be retracted by hand	Visual	

IK Representative	Client Representative
Date: Signature:	Date: Signature:

4.5 PUNCH LIST AND NOTES FROM THE FAT

Table 10 – Punch List and Notes from the FAT

Action / Note	Starting Date and Responsible	Finishing Date and signature

5 SAFE JOB ANALYSIS (SJA)

This section of the document is the Safe Job Analysis, which is based and prepared in accordance with Norwegian Oil &Gas recommended guidelines for Common Model for Safe Job Analyses

SJA shall be conducted prior to testing and operation.

*Norwegian Oil &Gas recommended guidelines for Common Model for Safe Job Analyses to be included in Reference Documents table (*Table 1 - Reference Documents)*.- not included*

5.1 GUIDELINES FOR PLANNING AND PERFORMING SJA

SJA planned and carried out according to the main steps in the flow diagram below.

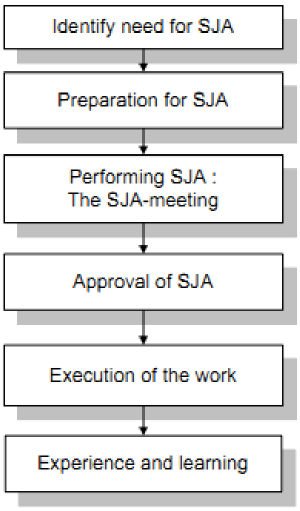


Figure 5 - SJA process flow

Package/ Project Title:	Polyurethane sealing discs on cleaning pigs; characterization and dynamic behavior
Document Title:	Test Procedure
IK Document No:	20825-IK-Z-KA-0001

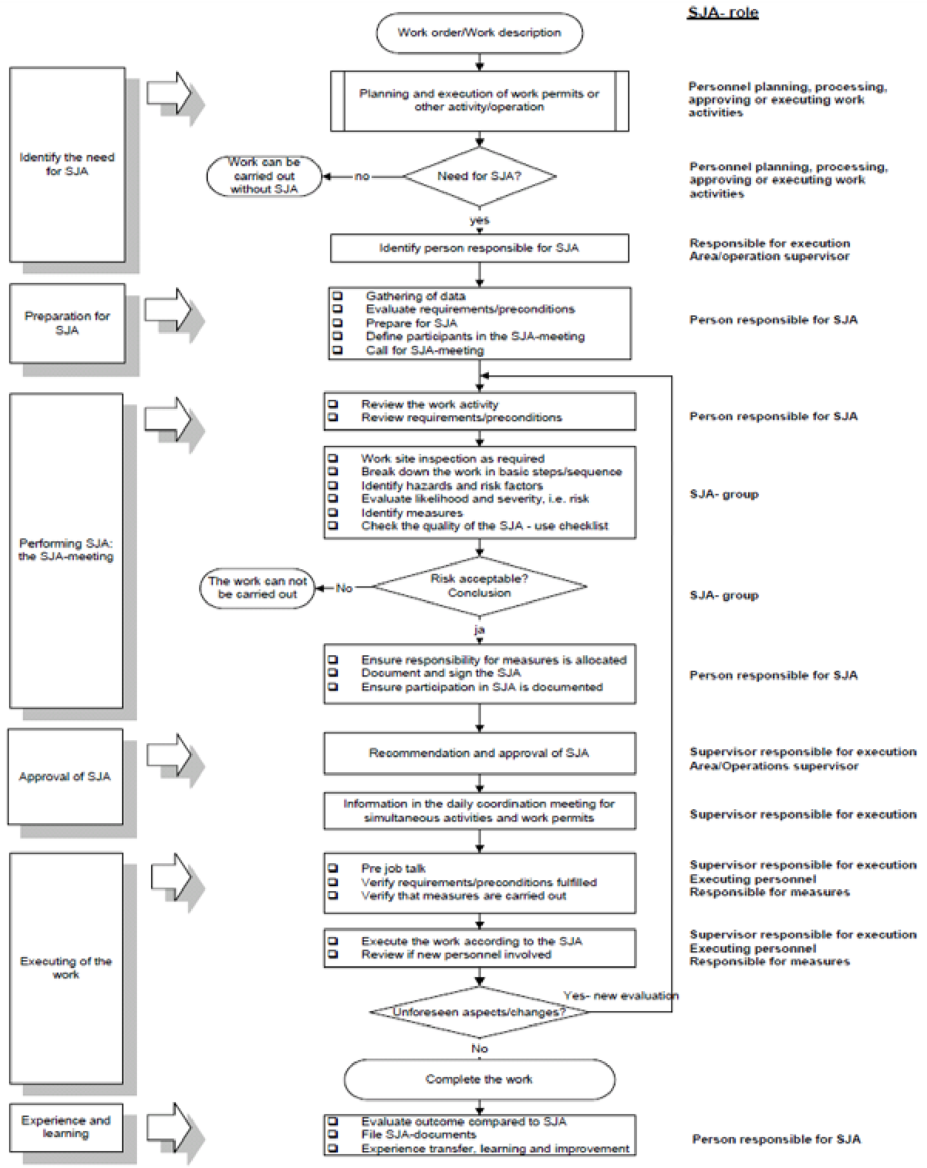


Figure 6 - SJA detailed process flow

5.2 PPE WEARING REQUIREMENTS

PPE - Personnel performing the test

Personnel performing the test shall at all-time wear protective glasses, gloves, coverall, helmet and protective boots.

Ear protection such as plugs shall be used during operation of noisy equipment.

PPE - Personnel observing the test

Personnel observing the test shall at all-time as a minimum wear protective glasses, helmet and protective boots. Coveralls will be available on request.

Each person is responsible for using personal protective equipment.

5.3 STANDARD SJA FORM

Table 11 - Standard SJA form

SJA title:			**SJA No.:**	**Department/Discipline:**	**Person responsible for SJA:**
Description of the work:				**Installation:** **Area/Module/Deck:**	**Tag/line no.:**
Requirements/Preconditions:				**WP/WO no.:**	**Number of attachment:**
No	**Basic Steps**	**Hazard/Cause**	**Potential Consequence**	**Measurement**	**Responsible**
1.					
2.					
3.					
4.					
5.					
6.					
Is the total risk acceptable: (Yes/No)?		**Approval**	**Date/Signature**	**Checklist for SJA applied (Tick off)**	
		SJA Responsible		**Summary of experience after completion of work:**	
Conclusion/Comments:		**Responsible for execution**			
		Area/Operations supervisor			
		Other positions			

5.4 RISK EVALUATION. RISK MATRIX

In some cases it may be beneficial for the SJA group to use a risk matrix to assess the risks associated with hazard and so we can relate the likelihood of a hazard happening and the severity of the consequences. Such assessments can be used to clarify the need for measures and to prioritize actions to be taken. The assessment is a rough approximation. High-risk hazards identified could be subject to a more detailed assessment later. A risk matrix is used to assess the risk by plotting the probability or likelihood on one axis and the consequences or severity on the other. This is done for each step or task, as listed in the SJA form. If the combination or likelihood, according to the matrix, is medium or high, measures will be required. The individual operating companies will normally have their own matrix used in risk analysis, but a simplified matrix like the one given below with three levels of likelihood and three levels of severity, may be useful when performing SJA.

Table 12 - Grade of Consequences / Probabilities

Grade of Consequences	Explanation
High	Fatality, major injury or illness, significant pollution, significant equipment damage, significant amount of deferred production, significant gas/oil leak, impairment of the safety integrity of the installation or part of the installation.
Medium	Lost-time injury or minor injury, minor pollution, minor equipment damage, minor amount of deferred production, minor gas/oil leak, impairment of the safety integrity of a part of the installation (like a module)
Low	No injury, superficial equipment damage or pollution, insignificant amount of deferred production, insignificant gas/oil leak, local or negligible impairment to the safety integrity of the installation.

Grade of Probabilities	Explanation
High	Probable, likely to occur several times during a year.
Medium	Possible, could occur sometimes, the incident has occurred on the installation
Low	Remote likelihood, unlikely though conceivable, the incident has occurred in the industry

	Probability		
Consequence	**Low**	**Medium**	**High**
Low	Low	Low	Medium
Medium	Low	Medium	High
High	Medium	High	High

Package/ Project Title:	'Polyurethane sealing discs on cleaning pigs; characterization and dynamic behavior
Document Title:	Test Procedure
IK Document No:	20825-IK-Z-KA-0001

Table 13 - Risk Matrix

No.	Basic Step	Consequence	Probability	Evaluation
1.				
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9.				
10.				

Package/ Project Title:	'Polyurethane sealing discs on cleaning pigs; characterization and dynamic behavior	
Document Title:	Test Procedure	
IK Document No:	20825-IK-Z-KA-0001	

5.5 STANDARD SAFE JOB ANALYSIS CHECKLIST

Table 14 - Standard SJA Checklist

No	Checklist for SJA No: SJA Title:	Taken care off?			Comments
		Yes	No	N/A	
A	**Documentation and experience**				
1	Is this a familiar work operation for the crew?				
2	Is there an adequate procedure/instruction/work package?				
3	Is the group aware of experiences/ incidents from similar activities/SJA?				
B	**Competence**				
1	Do we have the necessary personnel and skills for the job?				
2	Are there other parties that should participate in the SJA meeting?				
C	**Communication and coordination**				
1	Is this a job where several units/crews must be coordinated?				
2	Is good communications and suitable means of communication in place?				
3	Are there potential conflicts with simultaneous activities (system/area/ installation)?				
4	Has it been made clear who is in charge for the work?				
5	Has sufficient time been allowed for the planning of the activities?				
6	Has the team considered handling of alarm/emergency situations and informed emergency functions about possible measures/actions?				
D	**Key physical safety systems**				
1	Are barriers, to reduce the likelihood of unwanted release/leakage maintained intact (safety valve, pipe, vessel, control system etc.)?				
2	Are barriers, to reduce the likelihood of the ignition of a HC leakage maintained intact (detection, overpressure protection, isolation of ignition sources etc.)?				
3	Are barriers to isolate leakage sources/lead hydrocarbons to safe location maintained intact (process/emergency shutdown system, blowdown system, x-mastree, drains etc.)?				
4	Are barriers to extinguish or limit extent/spread of fire/explosion maintained intact (detection/ alarm, fire pump, extinguishing system/equipment etc.)?				
5	Are barriers to provide safe evacuation of personnel maintained intact (emergency power/lightning, alarm/PA, escape-ways, lifeboats etc.)?				
6	Are barriers that provide stability to floating installations maintained intact (bulkheads/doors, open tanks, ballast pumps etc.)?				
E	**Equipment worked on/involved in the job**				
1	Is the necessary isolation from energy provided (rotation, pressure, electrical voltage etc.)?				
2	May high temperature represent a danger?				
3	Is there sufficient machinery protection/shields?				
F	**Equipment for the execution of the job**				
1	Is lifting equipment, special tools, equipment/material for the job available, familiar to the users, checked and found in order?				
2	Do the involved personnel have proper and adequate protective equipment?				
3	Is there danger of uncontrolled movement/rotation of equipment/tools?				
G	**The area**				
1	Is it necessary to make a worksite inspection to verify access, knowledge about the working area working conditions etc.?				
2	Has work at heights/at several levels above each other/falling objects been considered?				
3	Has flammable gas/liquid/material in the area been considered?				
4	Has possible exposure to noise, vibration, poisonous gas/liquid, smoke, dust, vapour, chemicals, solvents or radioactive substances been considered?				/Use Ear Protection/
H	**The workplace**				
1	Is the workplace clean and tidy?				
2	Has the need for tags/signs/barriers been considered?				
3	Has the need for transportation to/from the workplace been considered?				
4	Has the need for additional guards/watches been considered?				
5	Has weather, wind, waves, visibility and light been considered?				
6	Has access/escape been considered?				
7	Has difficult working positions, potential for work related diseases been considered?				
I	**Additional local questions**				
1	Has the system sufficient protection towards rotating parts?				

5.6 SJA Participants List

Table 15 - SJA Participant list

SJA PARTICIPANT LIST	SJA TITLE:						SJA No:
SJA Meeting Date:________ Time:________ Place:________ SJA-responsible:________				Signature when changing personnel etc.			
Name(Block letters)	Dep/Discipline	Date	Signature	Name(Block letters)	Dep/Discipline	Date	Signature

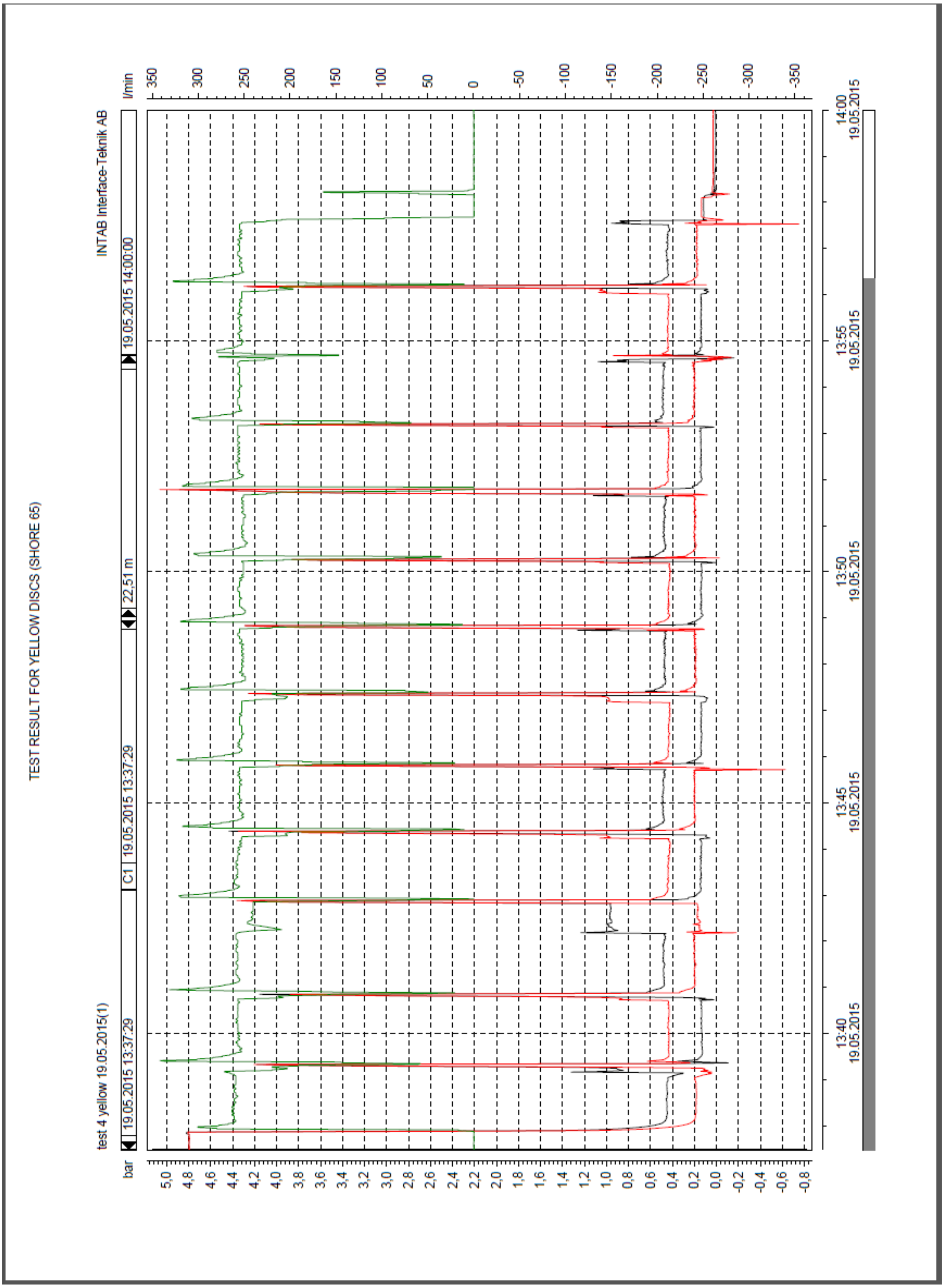
Package/ Project Title:	Production Flowline Pigs for BG Limited
Document Title:	FAT Procedure
IK Document No:	20825-IK-Z-KA-0001
BG Document No:	JB01-IKG-Z-KA-0001

5.7 SJA Punch List and Notes

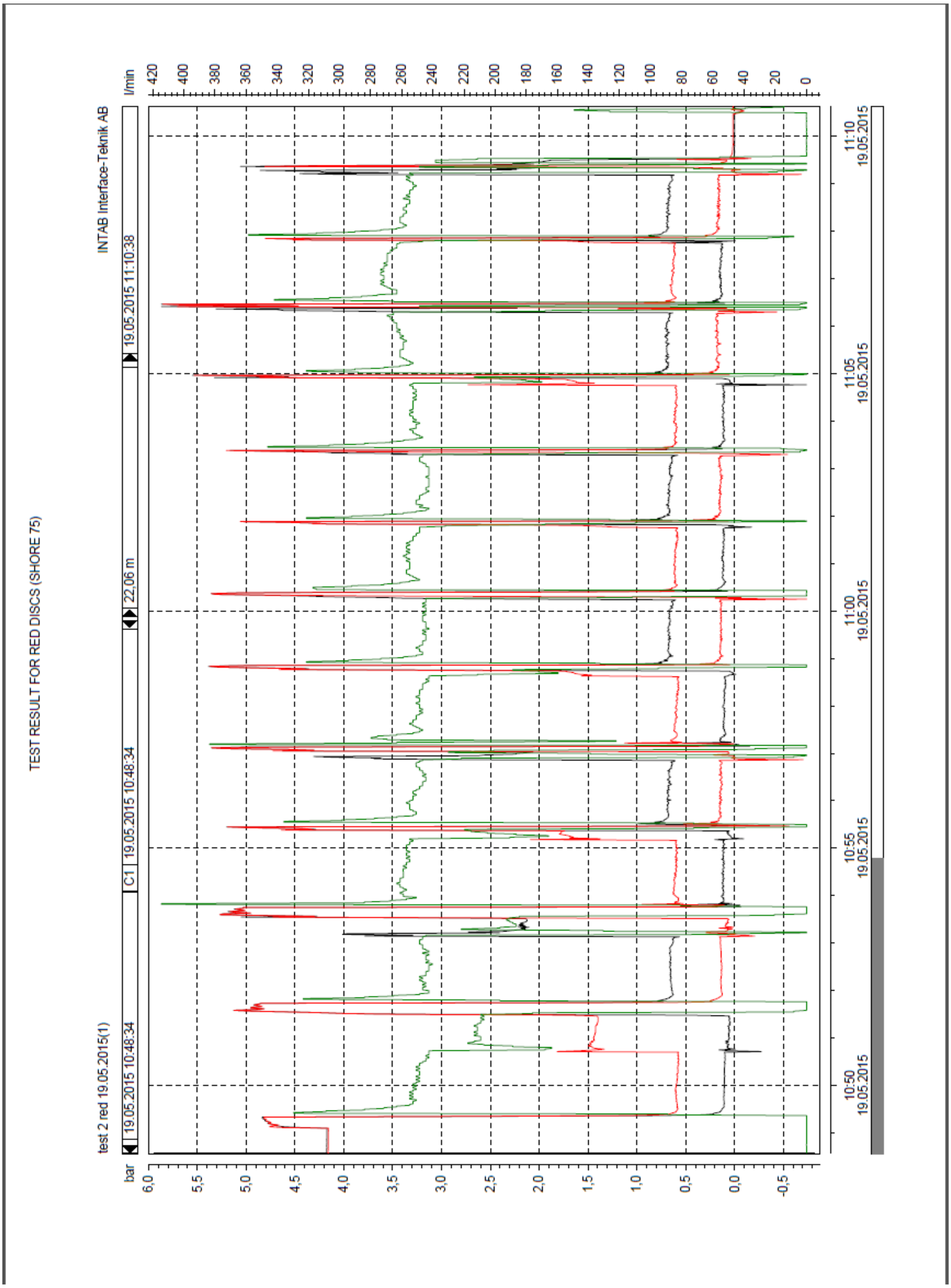
Table 16 - SJA Punch List and Notes

Pos.	Operation Task title	Identified Risk (Risk Description)	Potential Consequence	Action	Responsible for Action
1					
2					
3					
4					
5					

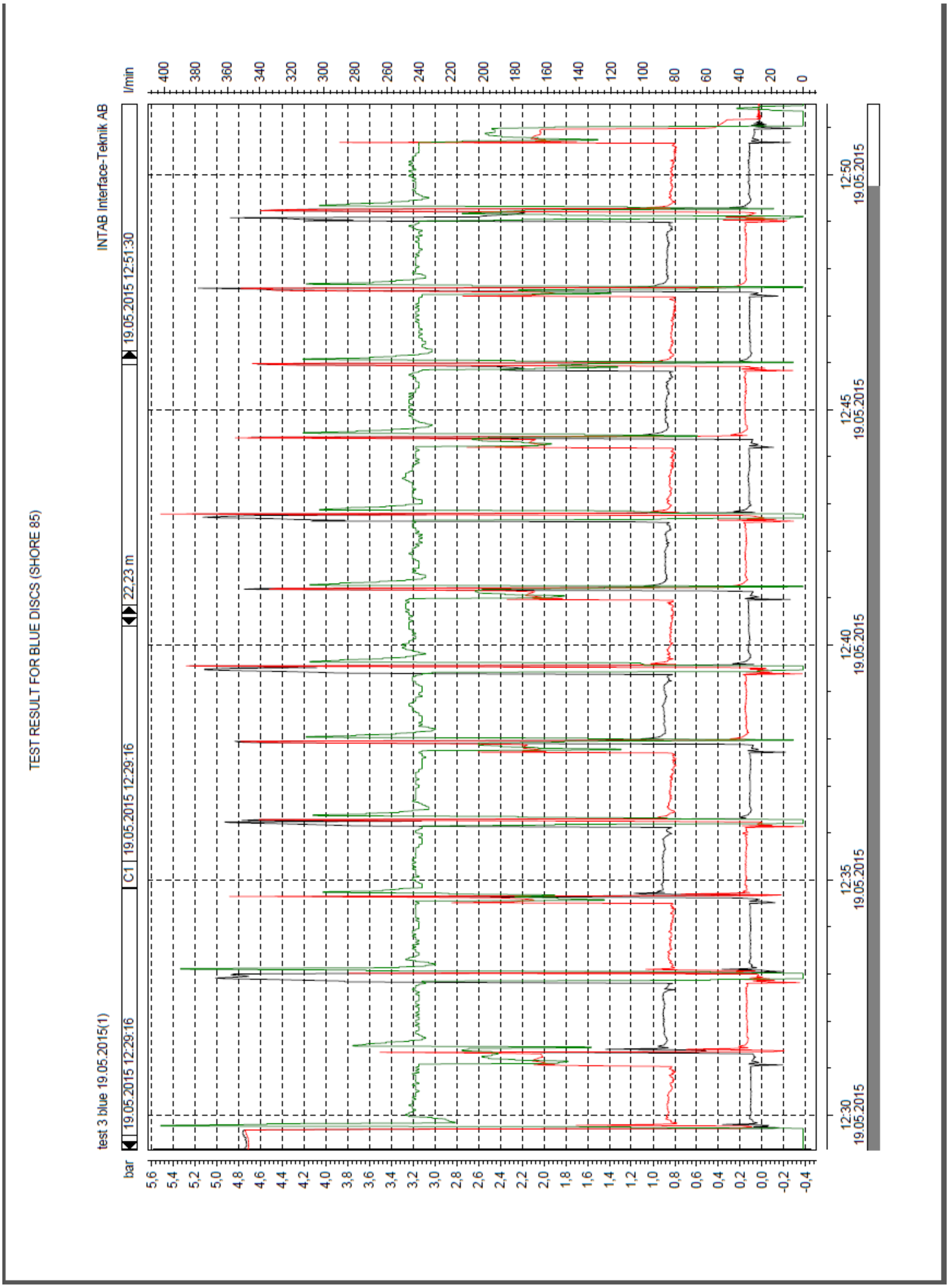
Appendix 8 Easyview record of pig travel time – Shore grade 65



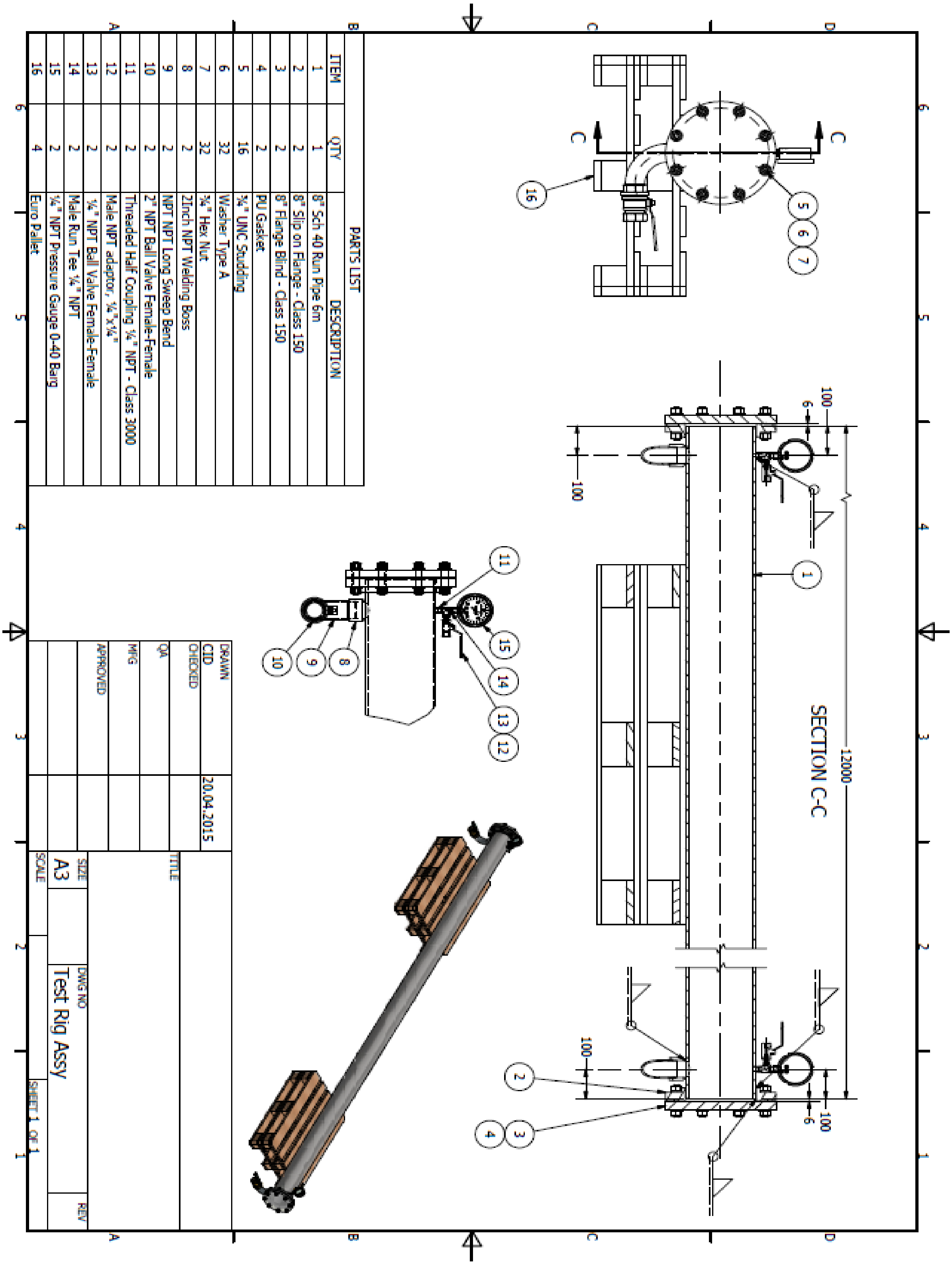
Appendix 8 Easyview record of pig travel time – Shore grade 75

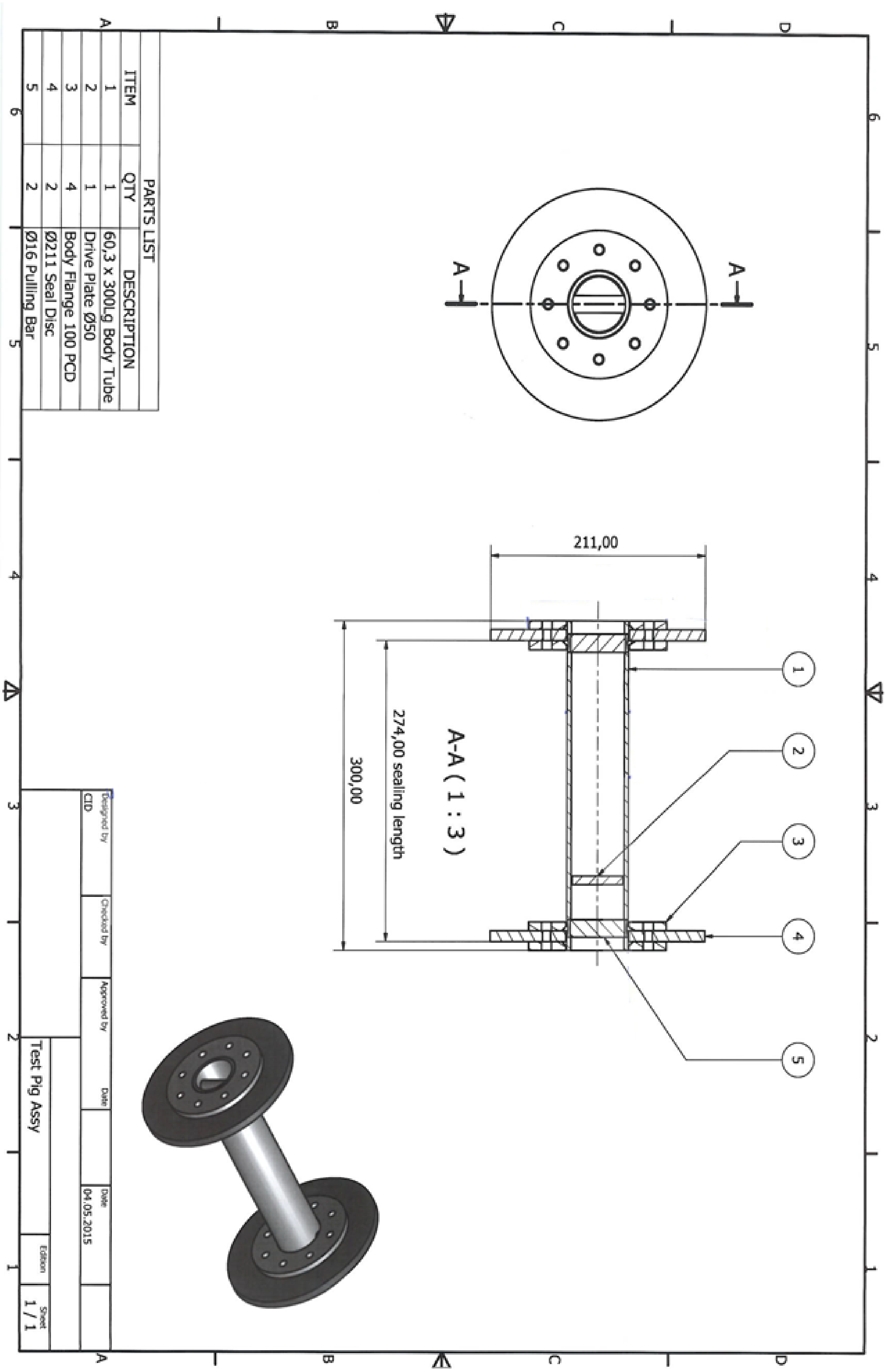


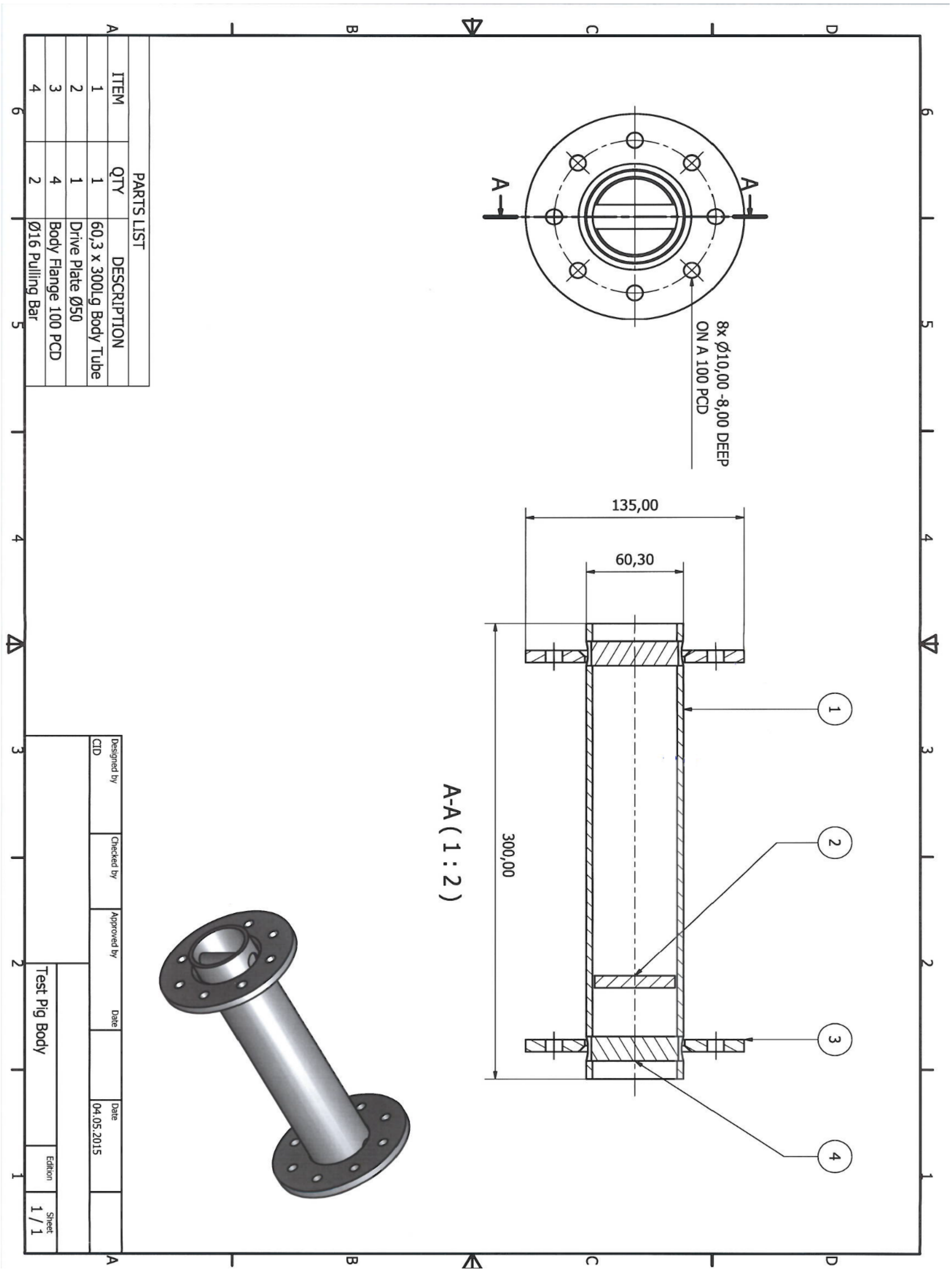
Appendix 8 Easyview record of pig travel time – Shore grade 85



Appendix 9 Detail drawing of test rig, and shore grade 65, 75, and 85 pig.




PARTS LIST
ITEM
QTY
DESCRIPTION
1 1 60,3 x 300Lg Body Tube
2 1 Drive Plate Ø50
3 4 Body Flange 100 PCD
4 2 Ø211 Seal Disc
5 2 Ø16 Pulling Bar
A-A
A-A (1 : 3)
211,00
274,00 sealing length
300,00
Designed by
CID
Checked by
Approved by
Date
Date
04.05.2015
Test Pig Assy
Edition
Sheet
1 / 1


PARTS LIST
ITEM QTY DESCRIPTION
1 1 60,3 x 300Lg Body Tube
2 1 Drive Plate Ø50
3 4 Body Flange 100 PCD
4 2 Ø16 Pulling Bar
A-A
8x Ø10,00 -8,00 DEEP
ON A 100 PCD
135,00
60,30
300,00
A-A (1 : 2)
1
2
3
4
Designed by
CID
Checked by
Approved by
Date
Date
04.05.2015
Test Pig Body
Edition
Sheet
1 / 1