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NON-INVASIVE PRESSURE MEASUREMENT

Bachelor Project

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Abstract

This report presents a study conducted to determine if an internal pressure can be measured using a strain gauge. The main reason for performing the study was to find a way to eliminate unnecessary flanged joints in piping at process plants. These unnecessary flanged joints are implemented into the piping to install instrumentation to measure the current pressure inside the pipe. Each flanged joint poses a concern regarding leakage. Thus each flanged joint is a safety matter. If the number of flanged joints can be reduced, the costs regarding this issue can be reduced significantly.

To outline this issue, a test was performed to determine if the internal pressure causes the pipe to expand enough to have a measureable strain on the pipe surface. Secondly, the instrumentation needed to commercialize a product using the idea was determined, mainly concerning the installation area in relation to the electrical systems. Thirdly, a simple controller was programmed in MATLAB combined with SIMULINK to enable compensation for a change in temperature. It is also able to change parameters in relation to material properties and wall thicknesses based on NORSOK piping specifications as it is now. The database of materials can be expanded so that the controller can be applied in a wider market concerning piping specifications and material properties.

Preface

This study is a feasibility study concerning if it is possible to use hoop stress calculation combined with strain gauges to determine the internal pressure of metal pipes.

The intention of the study is to:

1. Determine if it is possible to use hoop stress calculations combined with strain gauges to determine the internal pressure
2. Determine how the instrumentation should be if it is possible
3. Describe a simple controller, which can compensate for the change in temperature between the samples taken.

A warm thank you goes to:

- **FORCE TECHNOLOGY**, Esbjerg, for their engagement in including the project in their ongoing pressure testing
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Jesper Alexander Schøler Jepsen

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Abbreviations

Abbreviation	Description
ATEX	Atmosphere Explosives
CH	Channel
Cr	Chrome
DAQ	Data Acquisition
EX	External
HPHT	High Pressure High Temperature
IN	Input
LCTS	Low Temperature Carbon Steel
MATLAB	Matrix Laboratory
NI	National Instruments
NORSOK	Norsk Sokkels Konkuranseposisjon
PLC	Programmable Logic Controller
QTR	Quarter
SA	Refer to [1]
SCADA	Supervisory Control and Data Acquisition
SK	Refer to [1]
SS	Stainless Steel
VI	Virtual Interface
WA	Refer to [1]
WD	Refer to [1]
WK	Refer to [1]

Symbols

Description	Symbol	Unit (SI)
Circumferential strain, initial	c_0	[-]
Circumferential strain, at sample	c_1	[-]
Diameter	D	[mm]
Energy flow	Q	[W]
Length	L	[mm]
Length	dx	[mm]
Mean coefficient of thermal expansion	α	[°C]
Modulus of elasticity	E	[Pa]
Pressure	P	[Pa]
Radius	r	[mm]
Resistance (electrical)	R	[Ω]
Resistance (thermal)	R_t	[°C / W]
Specific thermal capacity	c	[J / kg °C]
Strain	ε	[-]
Stress	σ	[Pa]
Temperature	T	[°C]
Thermal conductivity	k	[W / m °C]
Voltage (voltage drop over a resistance)	v	[V]
Voltage (output)	V_o	[V]
Voltage (source)	V_s	[V]
Wall thickness	t	[mm]

1 Introduction and objective

Pressure measurement is a crucial part of a process plant. It determines some of the parameters under which the equipment and process operates. It is also a good indication of an eventual leakage, i.e. if there is an unexpected pressure drop between two measuring points. Leakage is an overall concern at process plants in oil and gas, because of the flanged joints, all presenting a potential leakage.

Measurements of temperatures and pressure inside pipes have previously been done on the inside of the pipe, leading to a need for flanged joints to incorporate equipment into the flowline. In recent time the temperature has increasingly been measured by attaching PT-100 sensors to the surface of the pipe and locally insulating the point of measurement to preserve as much energy at the pipe as possible, making the difference in temperature from the inside of the pipe to the surface almost zero. This reduces the number of needed flanges however; a better solution would be to remove the need for flanged joints entirely, as the problem is that for measuring pressure a non-invasive solution is needed.

At HPHT process plants the temperatures and pressures are high; they go up to 205 °C and 1380 barg at the well. [2] The concerns regarding flanged joints are greater at higher temperature and pressure. This is due to the density of the gas being lower thus also lowering the particle size of the gas, giving possibility for leakage at flanges that are not properly sealed.

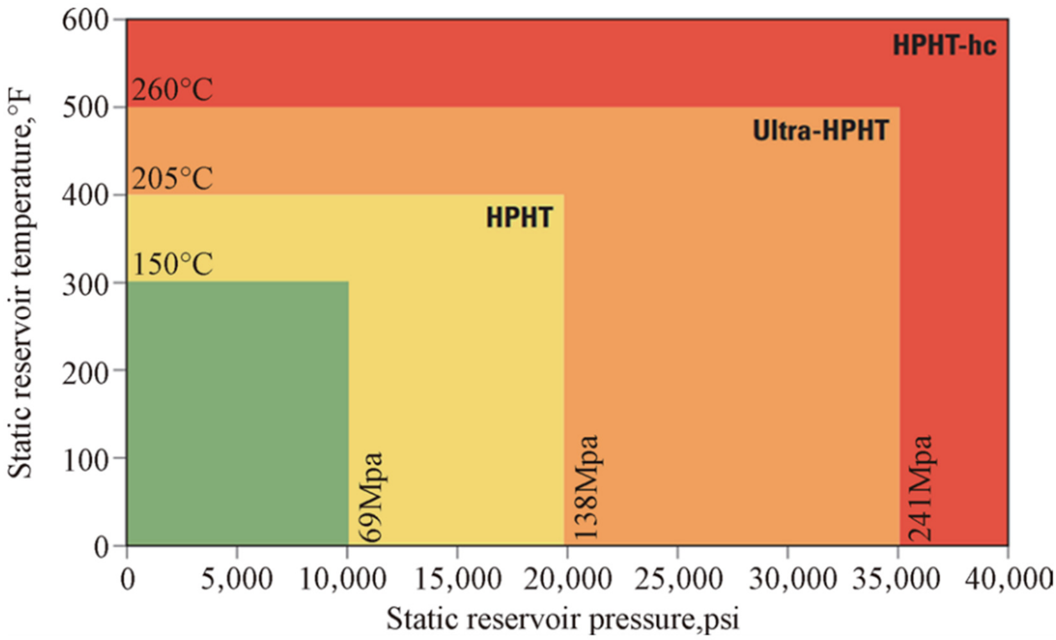

Figure 1-1: Reservoir pressure in relation to temperature for HPHT wells [2]

Figure 1-1 illustrates normal and the three different HPHT reservoir conditions:

			Temperature region [°C]	Pressure region [bar]
•	Green	Normal	< 150	< 690
•	Yellow	HPHT	150 – 205	690 – 1380
•	Orange	Ultra-HPHT	205 – 260	1380 – 2410
•	Red	HPHT-hc (extreme HPHT)	260 <	2410 <

1.1 Fields with HPHT conditions

Hejre is one of the HPHT fields in the Danish sector. It has a reservoir pressure of 1010 bar and a temperature of 160 °C. From Hejre, gas is lead to Syd Arne and oil is lead to Gorm E. From these platforms, gas and oil is lead to Nybro gas plant, which is an onshore facility. At Nybro, the gas will undergo further processing, if needed. Before it is lead to consumers, the oil is lead to the oil terminal in Frederica where it will undergo further processing if needed. When Hejre is operational, in 2018 according to plan, it will contribute to Denmark being self-sufficient on oil and gas. [3]

The largest new field that has been sanctioned in more than 25 years is Culzean. It is located in the UK North Sea sector. Studies have shown that this gas field will operate in HPHT conditions. The expectation is that the field will produce 5 % of the total gas needed in UK in 2020/21. The expectation is also that the field will be able to produce an output from 2019 and at least 13 years. [4]

Seeing that HPHT fields are gaining a more significant share of the market the equipment to be used on these fields are starting to be a point of interest.

1.2 Why measure the pressure?

Pressure measurement contributes to personnel safety. Installation of pressure safety valves, blowdown valves, shutdown vales, etc., which are pressure controlled provide for the safety of both personnel and equipment. Secondly, pressure measurement also provides information to the process plant about the process. There are points in the process that needs a certain pressure in order to get chemical reactions to work, or to separate gas from fluid, e.g. at the separator, which separate crude into oil, gas, water and sand using heat and pressure.

The safety of equipment must be assured in accordance with API 14C [5]. This standard clarifies good practices when designing and installing pressure measurement equipment as well as valves with the purpose of securing personnel as well as equipment. API 14C also provides sheets to be checked off in terms of safety analysis.

1.3 Project objective, scope

The requirements for pressure measurement and the challenges related to the necessary flanged joints create a market for a non-invasive pressure measurement method. The implementation of such a method can remove some, if not all, the flanged joints that are used for instrumentation (not at valves). This present study concerns a strain gauge solution combined with a controller to produce a measurement device that can compensate for the variation in temperature when measuring the pressure.

The aim of the study was is to develop a methods that will work for temperatures up to 205 °C and pressure up to 1380 barg, mainly the temperature region from 150-205 °C and the pressure region from 690-1380 barg, i.e. HPHT conditions.. However, the test conditions are limited to a working pressure of up to 680 barg due to the overpressure valve at the test facility. Secondly, due to need for simplification of the study in relation to the test, the temperature was kept constant at room temperature, i.e. approximately 20 °C during the test. This changes the parameters of the controller concerning the material properties in relation to wall thickness; therefore, the controller is for lower pressures than the HPHT conditions as this is more comparable to the test results, i.e. piping specifications that go up to 680 barg.

1.3.1 Objectives

The study will be in three parts with three areas of interest:

1. Identifying common piping materials and their thermal and mechanical properties, which are relevant in relation to this study.
    a. Is it possible to obtain equations for the needed properties?

2. Is it possible to measurement the pressure using a strain gauge attached to the outside of a pipe to determine the pressure inside the pipe?
    a. As stated above, the strain gauge will be attached either directly to the pipe or onto a clamp-on solution. This will result in a measureable strain. The question is then, at what pressure regions is it possible to detect a strain?
3. How should the instrumentation be implemented in relation to maintainability, data collection and safety?
    a. What additions are needed to obtain the needed data for the controller, e.g. temperature measurement?
    b. What are the safety requirements at a HPHT process plant? What characteristics should the instrumentation possess to meet these requirements?
4. How will a simple controller look like which can determine the internal pressure of a pipe, in relation to hoop stress? In addition, is it possible to compensate thermal expansion?
    a. Which factors influence the strain from the inside to the outside surface of the pipe? How can these influences be modelled into a controller using e.g. SIMULINK?

2 Piping material and properties

This chapter covers commonly used piping materials and their properties, both mechanical and thermal to give an overview of these. These properties are needed to model the controller in order to have an accurate determination of the pressure as the temperature many fluctuate.

Piping material and wall thicknesses can be classified according to the working pressure of a given pipe, the standards to illustrate this classification is different from company to company. The only common this that the numbering/lettering is based on material and pound class. Some companies use their own piping specification classification, e.g. Maersk and HESS. Others base it on standards such as NORSOK L-001 [6]. This standard uses lettering and numbering define materials and pound classes, see Appendix 1. It also lists the wall thickness for each piping class, according to material, pound class and nominal diameter. The list can be found in Appendix 2. The materials specified through L-001 are found in NORSOK M-630 [7], and are for piping specification classes:

- **C11** - A333, grade 6 (LTCS), UNS: K03006, material no. 1.0456
- **S20** - A312, TP316 (SS), UNS: S31600, material no. 1.4401
- **D20** - A790/A928, S31803 (duplex 22 Cr), UNS: S31803, material no. 1.4462
- **D30** - A790/A928, S32750 (super duplex 25 Cr), UNS S32750, material no. 2.4660

For the materials, the specific thermal capacity, thermal conductivity, mean coefficient of thermal expansion and modulus of elasticity will be variables in accordance to temperature. These values are determined by using formulas, which are based on tendency lines created by using the values given in Appendix 3 which list material properties based on data from [8]. This is done to be able to determine each value at each given temperature as exact as possible for usage in the controller (see section 5.4).

Specific thermal capacity, *c* [J/kg °C] [9]

K03006	$c = -2 \cdot 10^{-14} \cdot T^6 + 4 \cdot 10^{-11} \cdot T^5 - 2 \cdot 10^{-8} \cdot T^4 + 7 \cdot 10^{-6} \cdot T^3 - 0{,}0015 \cdot T^2 + 0{,}549 \cdot T + 450{,}79$ $R^2 = 1$
S31600	$c = -2 \cdot 10^{-15} \cdot T^6 + 4 \cdot 10^{-12} \cdot T^5 - 2 \cdot 10^{-9} \cdot T^4 + 4 \cdot 10^{-7} \cdot T^3 - 0{,}0007 \cdot T^2 + 0{,}5606 \cdot T + 440{,}16$ $R^2 = 0{,}9998$
S31803	$c = 474{,}51 \cdot e^{0{,}0005 \cdot T}$ $R^2 = 0{,}9929$
S32750	$c = 476{,}4 \cdot e^{0{,}0005 \cdot T}$ $R^2 = 0{,}9961$

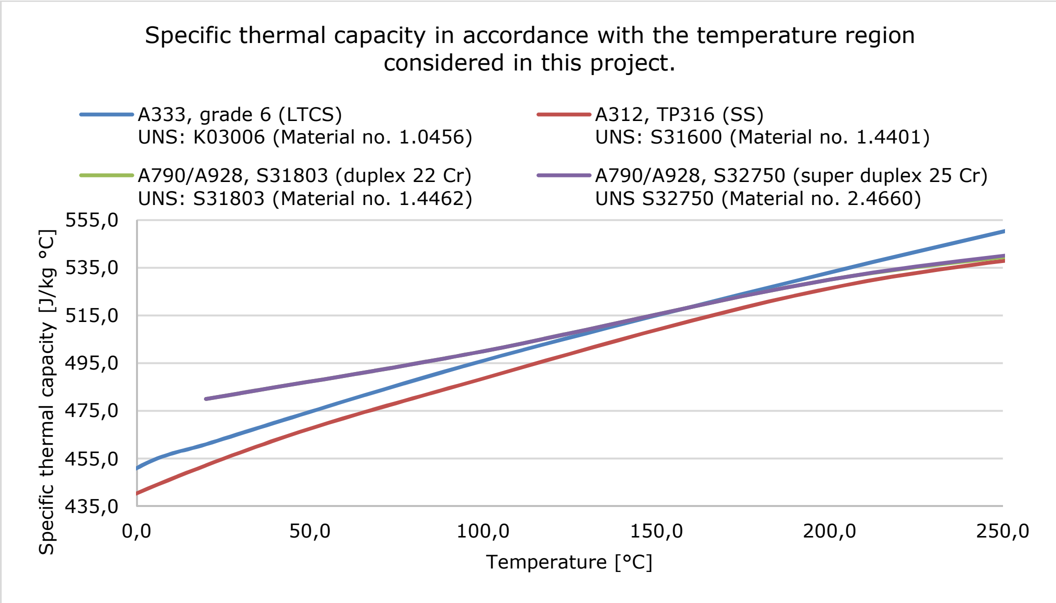

Figure 2-1: Specific thermal capacity as a function of temperature change [8]

The specific thermal capacity is a number indicating how much energy is needed to raise the temperature of one kilogram of a given material one degree.

Thermal conductivity, k [W/m °C] [9]

K03006	$k = -4 \cdot 10^{-16} \cdot T^6 + 1 \cdot 10^{-12} \cdot T^5 - 2 \cdot 10^{-9} \cdot T^4 + 1 \cdot 10^{-6} \cdot T^3 - 0{,}0003 \cdot T^2 - 0{,}0066 \cdot T + 60{,}661$ $R^2 = 1$
S31600	$k = 0{,}0143 \cdot T + 13{,}964$ $R^2 = 0{,}9996$
S31803	$k = 0{,}0143 \cdot T + 13{,}964$ $R^2 = 0{,}9996$
S32750	$k = 0{,}0143 \cdot T + 13{,}964$ $R^2 = 0{,}9996$

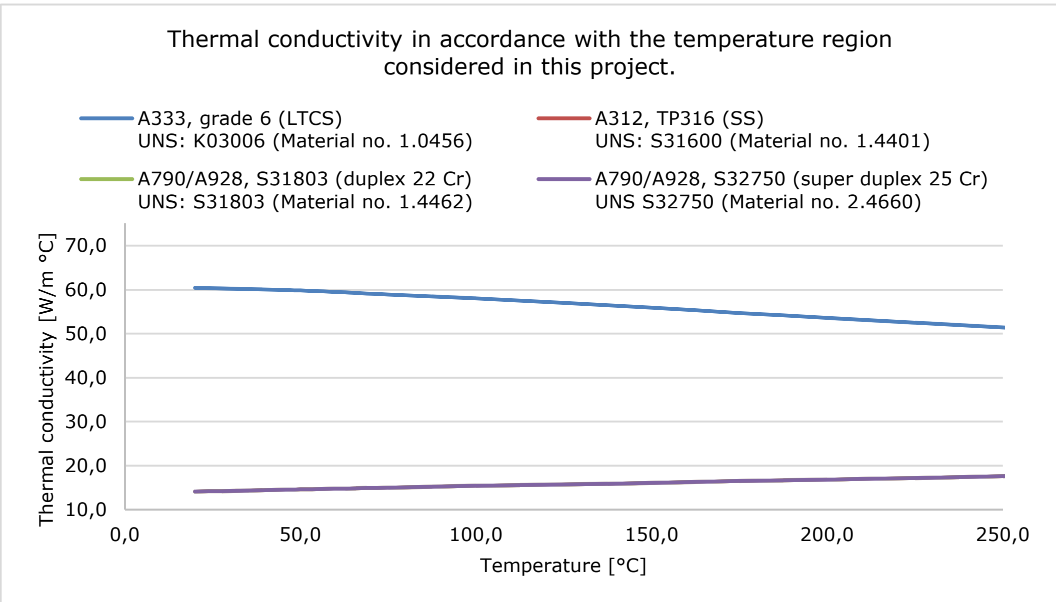

Figure 2-2: Thermal conductivity as a function of temperature change [8]

Thermal conductivity is a measure for the amount of energy that can be transferred through a given thickness of a material at a given temperature of said material. Materials with low thermal conductivity are insulators, e.g. foams, rock wool, air. Materials with high thermal conductivity are, on the other hand, useful to transfer heat from one medium to another, e.g. the cooler of a car or a refrigerator.

	Mean coefficient of thermal expansion α [10^{-6} °C] [9]
K03006	$\alpha = 8 \cdot 10^{-17} \cdot T^6 - 2 \cdot 10^{-13} \cdot T^5 + 1 \cdot 10^{-10} \cdot T^4 - 3 \cdot 10^{-8} \cdot T^3 - 4 \cdot 10^{-6} \cdot T^2 + 0{,}008 \cdot T + 11{,}362$ $R^2 = 0{,}9995$
S31600	$\alpha = -1 \cdot 10^{-16} \cdot T^6 + 2 \cdot 10^{-13} \cdot T^5 - 1 \cdot 10^{-10} \cdot T^4 + 4 \cdot 10^{-8} \cdot T^3 - 2 \cdot 10^{-6} \cdot T^2 + 0{,}0123 \cdot T + 15{,}051$ $R^2 = 0{,}9997$
S31803	$\alpha = -3 \cdot 10^{-6} \cdot T^2 + 0{,}0058 \cdot T + 12{,}536$ $R^2 = 0{,}9988$
S32750	$\alpha = -3 \cdot 10^{-6} \cdot T^2 + 0{,}0058 \cdot T + 12{,}536$ $R^2 = 0{,}9988$

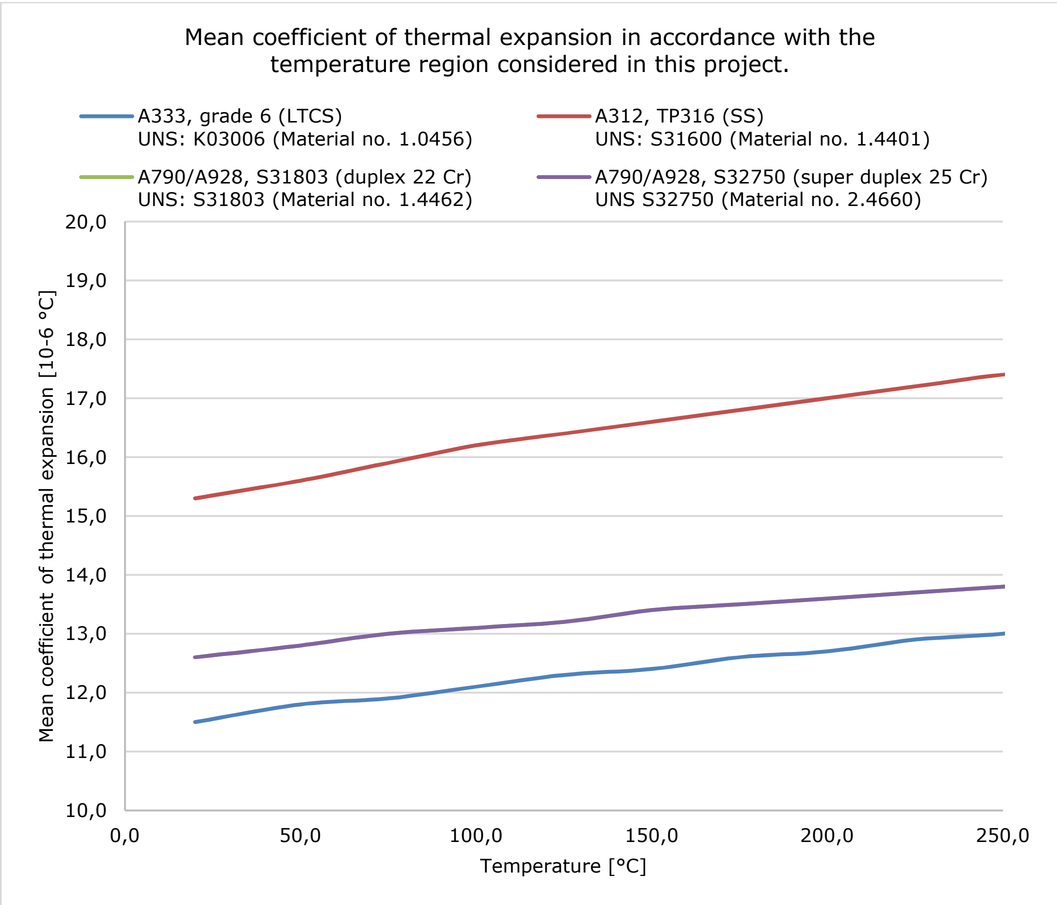

Figure 2-3: The mean coefficient of thermal expansion as a function of temperature change [8]

The mean coefficient of thermal expansion indicates how much the material expands when heated. Materials with a higher thermal expansion tend be less elastic than the materials that has a lower thermal expansion coefficient.

	Modulus of elasticity E [GPa] [9]
K03006	$E = 7 \cdot 10^{-17} \cdot T^6 + 1 \cdot 10^{-12} \cdot T^5 - 1 \cdot 10^{-9} \cdot T^4 + 1 \cdot 10^{-7} \cdot T^3 + 6 \cdot 10^{-5} \cdot T^2 - 0{,}0646 \cdot T + 203{,}66$ $R^2 = 0{,}9999$

S31600	$E = 2 \cdot 10^{-16} \cdot T^6 - 3 \cdot 10^{-13} \cdot T^5 + 7 \cdot 10^{-11} \cdot T^4 + 1 \cdot 10^{-8} \cdot T^3 - 1 \cdot 10^{-5} \cdot T^2 - 0{,}0656 \cdot T + 196{,}14$ $R^2 = 0{,}9998$
S31803	$E = 2 \cdot 10^{-15} \cdot T^6 - 8 \cdot 10^{-13} \cdot T^5 - 9 \cdot 10^{-10} \cdot T^4 + 2 \cdot 10^{-7} \cdot T^3 + 4 \cdot 10^{-5} \cdot T^2 - 0{,}0655 \cdot T + 201{,}82$ $R^2 = 0{,}9999$
S32750	$E = 2 \cdot 10^{-15} \cdot T^6 - 8 \cdot 10^{-13} \cdot T^5 - 9 \cdot 10^{-10} \cdot T^4 + 2 \cdot 10^{-7} \cdot T^3 + 4 \cdot 10^{-5} \cdot T^2 - 0{,}0655 \cdot T + 201{,}82$ $R^2 = 0{,}9999$

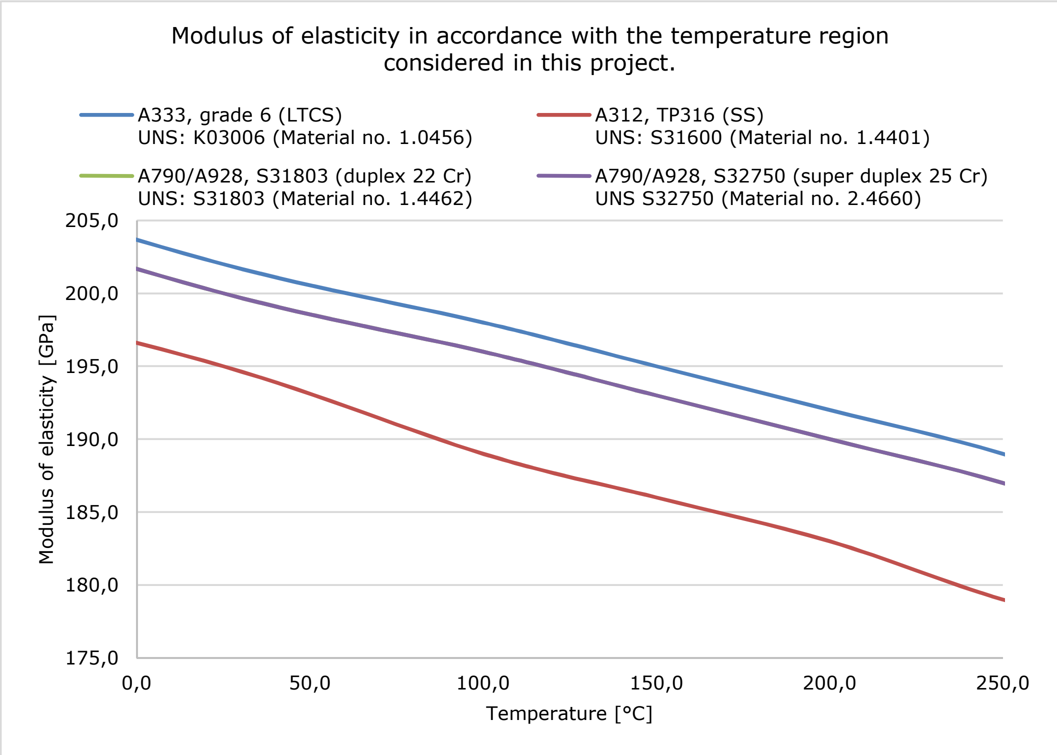

Figure 2-4: The modulus of elasticity as a function of temperature change [8]

The modulus of elasticity indicates how hard or soft a material is. Materials with low modulus of elasticity are harder than the ones with the higher elasticity. Materials with lower elasticity tend to be more brittle and have a higher risk of cracking.

3 Determining if the pressure is measureable

This chapter gives a brief analysis of strain gauge measurements in general and it accounts for the test made at FORCE TECHONOLOGY. It also describes the data which will be produced by the strain gauges at the testing facility. For the results of the tests to be actionable, these data must be collected for further processing.

The test was performed on two different pipe types to determine if the internal pressure causes a strain the outside of the pipe and if it does is it then the same irrespective of pipe type, i.e. is the linearity the same as hoop stress calculations. The test was conducted on the following two pipe types:

- Test 1: #150 LTCS 4" (wall thickness 6,02 mm)
- Test 2: #2500 LTCS 2" (wall thickness 11,07 mm)

3.1 Strain gauge measurements

Strain gauge measuring is performed using a Wheatstone bridge circuit. This circuit can be used in many ways to measure electrical resistance, e.g.

- Determination of absolute values of resistance by comparing it to a known resistance.
- Determination of a relative change in resistance.

The method is used to determine the change in resistance when measuring strain using a strain gauge. The relative change measureable using the Wheatstone bridge is as low as 10^{-4} Ω/Ω. Figure 3-1 illustrates a standard representation of a Wheatstone circuit. In the circuit, four resistances (R_1 to R_4), which are connected, form four branches. . The point between R_1 and R_4 (2) and the point between R_2 and R_3 (3) are dedicated for a voltage source (V_s) to be connected. The voltage output, which is also the output signal, can be measured at the point between R_1 and R_2 (1) and the point between R_3 and R_4 (4), (V_o). [10]

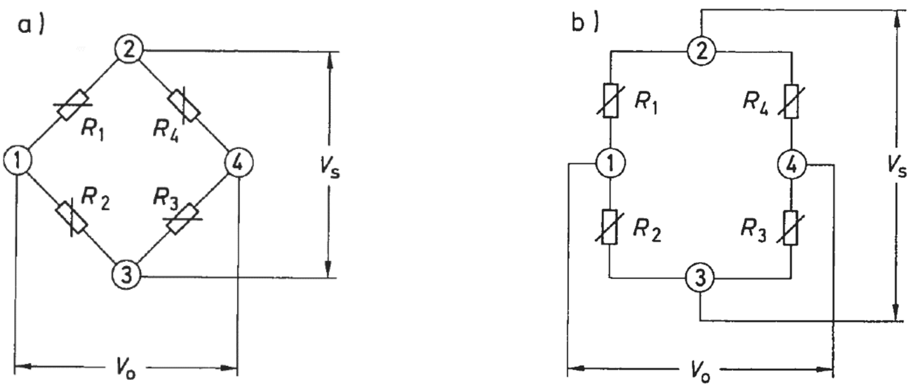

Figure 3-1: Wheatstone circuit representations [10]

When a voltage is applied to the points 2 and 3, the circuit will function as a voltage divider, leading to the following equations: [10]

$$v_1 = \frac{R_1}{R_1 + R_2} \cdot V_s \quad (3\text{-}1)$$

$$v_4 = \frac{R_4}{R_3 + R_4} \cdot V_s \quad (3\text{-}2)$$

These equations are also representatives for the output voltage at point 1 and 4. Equation 3-1 represent the voltage at point 1 and equation 3-2 represent the voltage at point 4. The measureable voltage difference can be derived from these two equations, see equation 3-3. This voltage is also the output voltage: [10]

$$V_o = V_s \cdot \left(\frac{R_1}{R_1 + R_2} - \frac{R_4}{R_3 + R_4}\right) = V_s \cdot (v_1 - v_4) \qquad 3\text{-}3$$

The equation can be rewritten to give an expression which covers the relation between the voltage output and voltage input: [10]

$$\frac{V_o}{V_s} = \frac{R_1}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} = \frac{R_1 \cdot R_3 - R_2 \cdot R_4}{(R_1 + R_2) \cdot (R_3 + R_4)} \qquad 3\text{-}4$$

From the formula, we see that there will not be a change in the output voltage if [10]:

$$R_1 = R_2 = R_3 = R_4 = R \qquad 3\text{-}5$$

$$\frac{R_1}{R_2} = \frac{R_4}{R_3} \qquad 3\text{-}6$$

If there is a change in the bridge resistors by a value of ΔR then the circuit becomes unbalanced and an output voltage can be measured between the points 1 and 4. This also leads to a change in equation 3-4: [10]

$$\frac{V_o}{V_s} = \frac{R_1 + \Delta R_1}{R_1 + \Delta R_1 + R_2 + \Delta R_2} - \frac{R_4 + \Delta R_4}{R_3 + \Delta R_3 + R_4 + \Delta R_4} \qquad 3\text{-}7$$

The use of strain gauge techniques produces a very small change in the resistances, which leads to a simplification of equation 3-7: [10]

$$\frac{V_o}{V_s} = \frac{1}{4} \cdot \left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right) \qquad 3\text{-}8$$

This simplification indicates that a change in the relative resistance induces a change in the balance of system. Knowing that the sensitivity of a strain gauge is expressed by the relative change in resistance of a gauge divided by the strain, equation 3-8 can be rewritten so that it represents strains instead of resistances: [10]

$$\frac{V_o}{V_s} = \frac{k}{4} \cdot (\epsilon_1 - \epsilon_2 + \epsilon_3 - \epsilon_4) \qquad 3\text{-}9$$

Equations 3-8 and 3-9 show that the changes in resistance (and strains) contribute to the imbalance of the circuit, thus giving a measureable signal through the output voltage. The following effects can be derived based on the signs in the equations: [10]

- Positive indication if: $\varepsilon_1 > \varepsilon_2$ and/or $\varepsilon_3 > \varepsilon_4$
- Negative indication if: $\varepsilon_1 < \varepsilon_2$ and/or $\varepsilon_3 < \varepsilon_4$

The equations presume that all resistances in the circuit change, which is almost never the case. In experimental stress analysis it is mostly one or two of the resistances which change, secondly it also not all resistances which are switched to strain gauges. This leads some of the ways of completing a Wheatstone bridge using resistances and strain gauges, it can be done using a quarter bridge (Figure 3-2), half bridge (Figure 3-3), double quarter or diagonal bridge (Figure 3-4) and full bridge (Figure 3-5), these types are most common. [10]

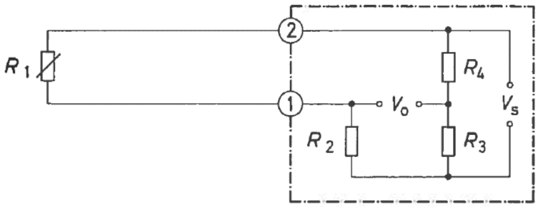

Figure 3-2: Quarter bridge [10]

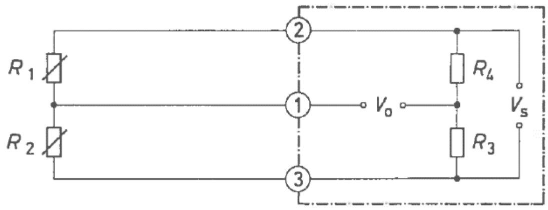

Figure 3-3: Half bridge [10]

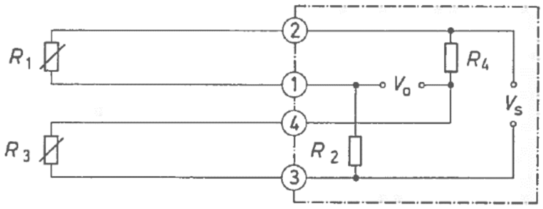

Figure 3-4: Double quarter or diagonal bridge [10]

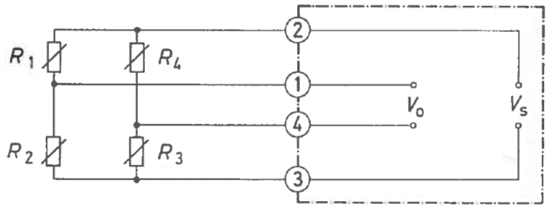

Figure 3-5: Full bridge [10]

Both of tests were performed using a quarter Wheatstone bridge for measurement see Figure 3-2, which only needs one strain gauge to be mounted to obtain an output.

3.2 Testing at FORCE TECHNOLOGY

The test at FROCE TECHNOLOGY was conducted on two different types of pipe to determine:

- If the pressure is measureable as a strain on the outside of the pipe on a high pound class and/or a low pound class
- How the strain develops in accordance with the internal pressure
- Linearity of each test - if it is present
- Some sort of factor that can relate the internal pressure to a strain, which can be converted back to pressure through a controller/compensator.

During test 1 the strain was measured both longitudinal and circumferential. During test 2 the strain was only measured circumferential but with two different types of strain gauges.

Figure 3-6 illustrates a principle drawing of the test setup used during both test. The water compressor pushes more water into the pipe to increase the pressure inside the pipe. The gauge pressure is a direct measurement of the current pressure.

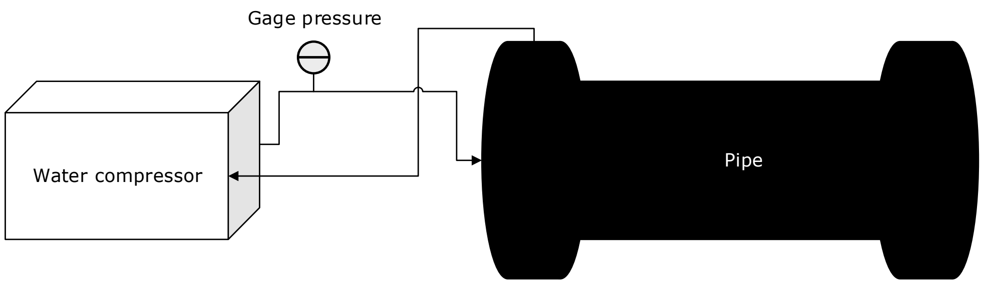

Figure 3-6: Principle drawing of the test setup

Figure 3-7 shows the low pound class pipe, #150. It is made of LTCS, the size of the pipe is 4'', and the piping specification class is AC11, according to NORSOK. The strain gauge attached to the pipe measures circumferential strain, another strain gauge is mounted perpendicular to it to measure longitudinal strain.

Figure 3-7: Test-1, Strain gauge for measuring circumferential strain

Figure 3-8 illustrates how the strain gauges are mounted on the pipe during test 1. Both strain gauges are of the same type (same as on shown on Figure 3-7). The gauges used are with fixed wireing instead of soldering wire. The main advantage of using a type with fixed wiring instead of soldering the wires to the based is that this type ensures a good connection to the base. The solder types do not ensure base connection since the connection is based on the way the soldering is performed.

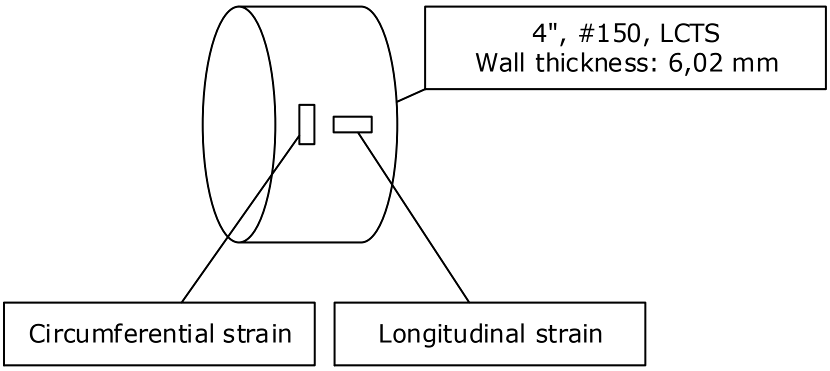

Figure 3-8: Illustration of how strain gauges are mounted during test 1

Each strain gauge have two wires that are to be wired to the acquisition terminals on a measuring collector (see Figure 3-9), which is connected to the computer through a patch cable. A program called LABVIEW, covered in section 3.2.1., process the acquired data.

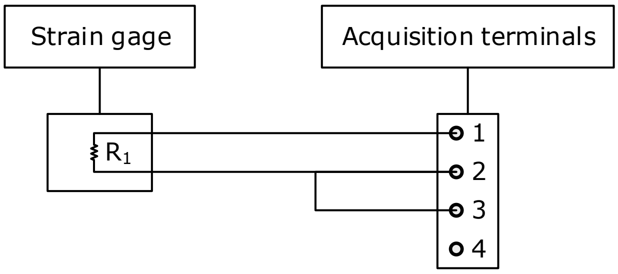

Figure 3-9: Wiring of strain gauge connection to data acquisition terminals

Test 2 was performed on a 2’’ #2500 pipe of NORSOK specification class GC11.. As stated earlier the strain gauges on this pipe both measure circumferential strain. The setup is illustrated in Figure 3-10.

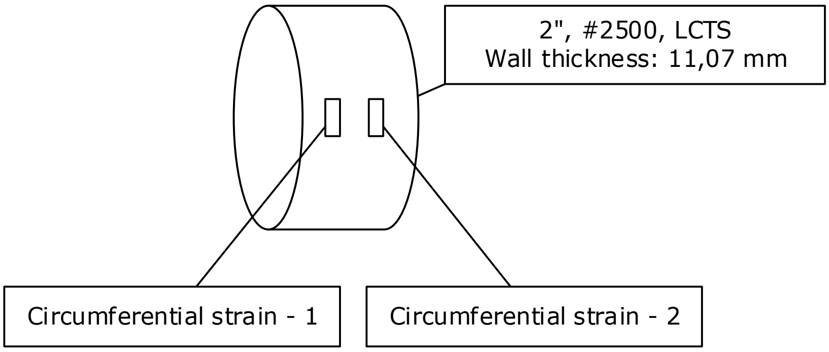

Figure 3-10: Illustration of how strain gauges are mounted during test 2

3.2.1 Data acquisition from strain gauge

A NI cDAQ-9178 acted as a data logger in order to obtain the measurements, see Figure 3-11. The measurement cables are located on the right side. The two cables on the left are for power and USB connection.

Figure 3-11: NI cDAQ-9178

This device is connected to the computer via USB and via a RJ50 cable connected to a NI 9944, (shown in Figure 3-12,) which is connected to the strain gauge. The RJ50 cables are the black cables on the right in Figure 3-11.

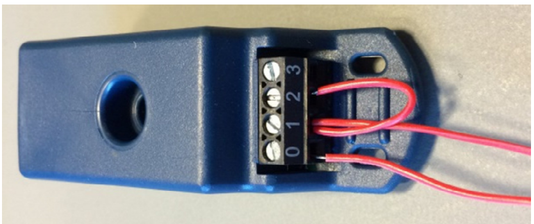

Figure 3-12: NI 9944

At the interface in LABVIEW, the configuraton of the NI9944 must be given at the "Strain Configuration". Asstated earlier, it is Quarter Bridge for the measurements in the project. The interface module chosen is a DAQ Assistant, which can be used to acquire or generate signals based on the settings made in LABVIEW. Figure 3-13 illustrates the configurations page of the DAQ Assistant for acquiring strain gauge measurements.

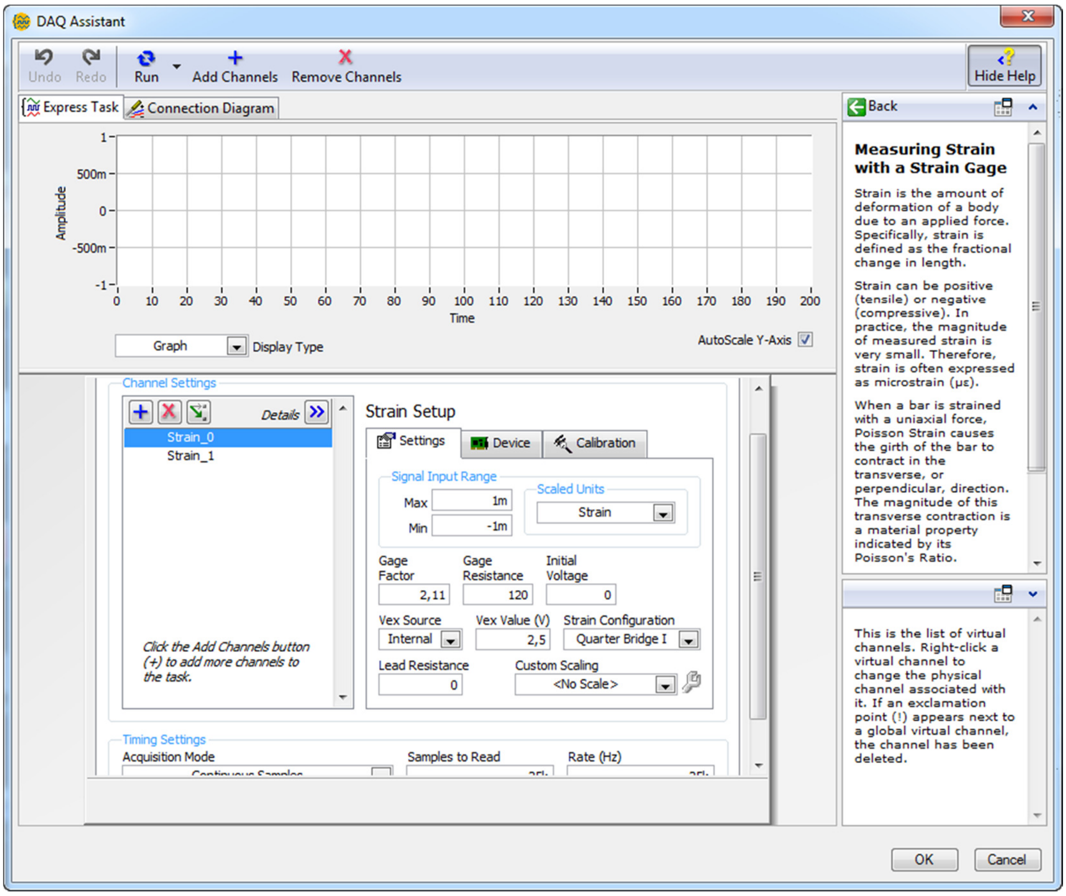

Figure 3-13: DAQ Assistant configuration

If the mouse is held over the "Strain Configuration", an illustration will appear at the bottom right of the picture. This illustration shows a principal diagram of the quarter bridge wiring (the mouse over picture is shown in Figure 3-14).

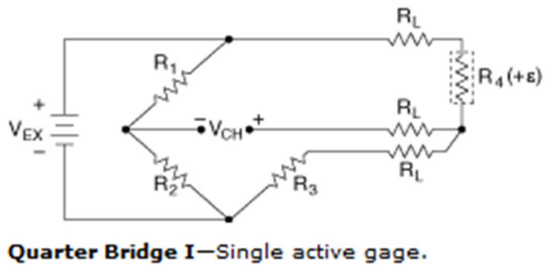

Figure 3-14: DAQ Assistant quarter bridge

The DAQ assistant also shows a how to connect the wire from the strain gauge to NI 9944, see Figure 3-15. When the wiring diagram is interpreted in accordance with the NI 9944 port numbering, this makes for the following assembly:

0. EX+: Strain gauge ½
1. IN+/CH+: Strain gauge ½ and Jumper leg ½
2. QTR: Jumper leg ½
3. Shield: Free (no shielding)

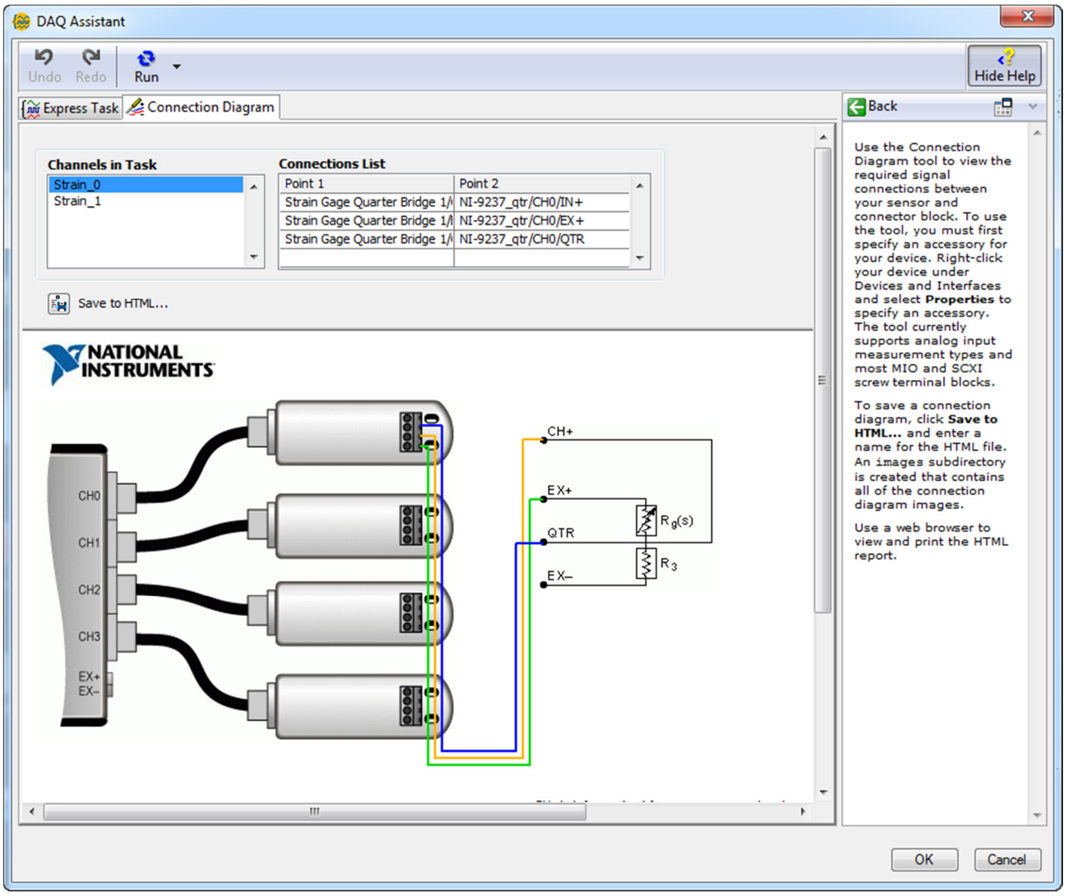

Figure 3-15: DAQ Assistant quarter bridge wiring

Once the system is wired and the strain gauges are calibrated to the correct values, a VI is chosen. These can be found through the menu in LABVIEW (help → Find examples → Enter keyword "strain" → select "Strain – Continuous input" → double click → Now strain gauge measurement VI appear in the VI-window, see Figure 3-16)

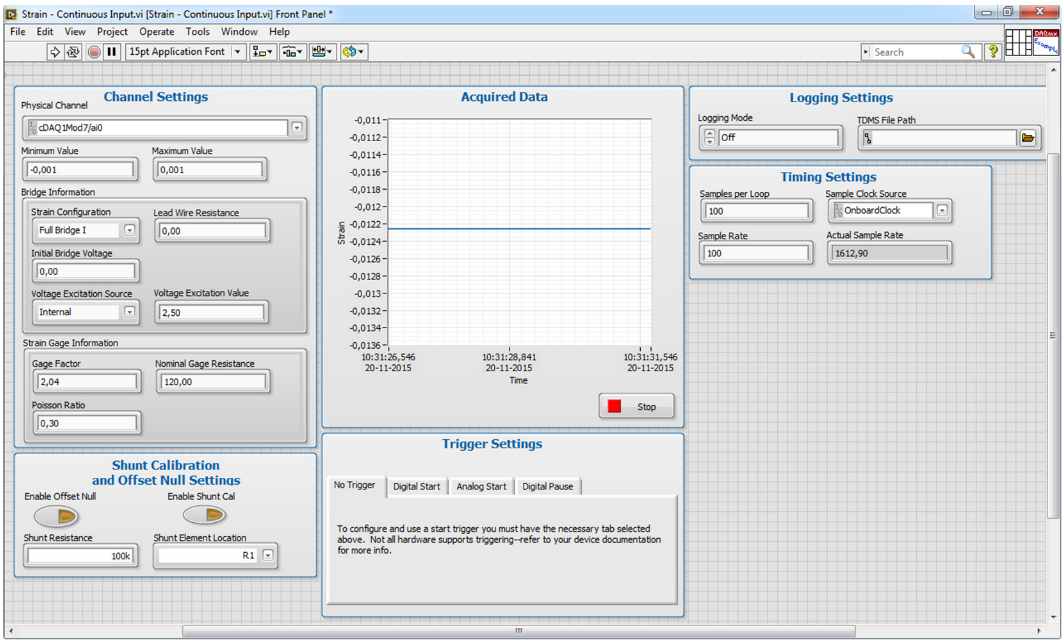

Figure 3-16: Strain gauge measurement VI

In the VI features setting windows, the DAQ settings can be configured, e.g. "Channel Settings" where the gauge factor and resistance can be changed, "Timing Settings" where the number of samples per loop and sample rate can be changed, etc.

3.2.2 Test results

The settings during the two tests were as follows:

- Gauge factor: 2,11
- Gauge resistance: 120
- Sample per loop: 100
- Sample rate: 100

This results in approximately 590000 samples for test 1 and 1120000 samples for test 2. Due to the massive number of samples and limited computing force, a simplifier has been made in MATLAB. The simplifier takes an average per 100 samples, i.e. reduces the number from 100 per second to one sample per second.

```
% Data simplifier. Made to reduce obtained data by the sample number.

close all
clear all
clc

%% Building matrix

% Building a matrix for circumferential strain
c=zeros(0)

% Building a matrix for longitudinal strain
l=zeros(0)

%%  Reducing matrix

n = 100; %Sample number
```

```
c1=size(c,1);
mc=c1-mod(c1,n);
y=reshape(c(1:mc),100,[]);

Result_c =transpose(sum(y,1)/n); %Simplified matrix (data reduction by the
number of samples)

l1=size(l,1);
ml=l1-mod(l1,n);
yl=reshape(l(1:ml),100,[]);

Result_l =transpose(sum(yl,1)/n); %Simplified matrix (data reduction by the
number of samples)
```

Data from both tests were run through the simplifier before further processing.

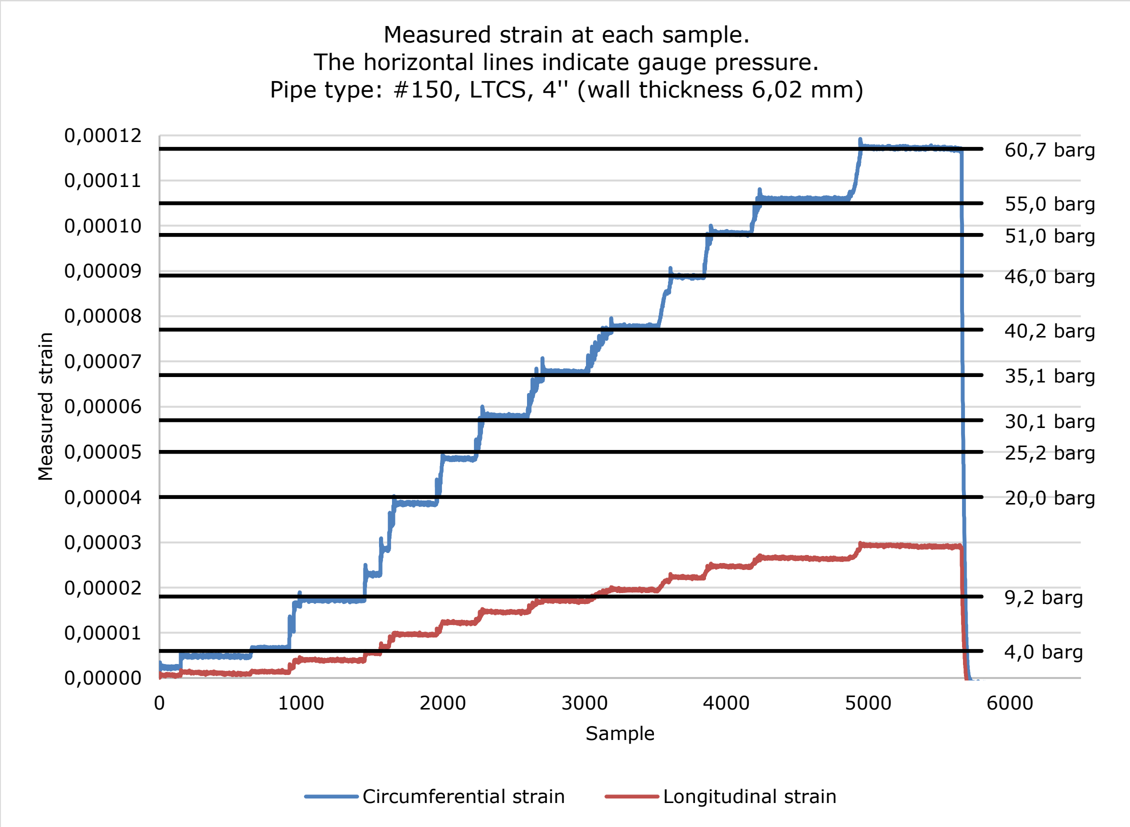

Figure 3-17: Experimental results from test 1, after the data have been processed through the simplifier

Figure 3-17 illustrates how the strain develops in accordance with a change in the gauge pressure. Test 1 was performed with two strain gauges, one measuring the circumferential strain and one measuring the longitudinal strain. The gauge pressure is illustrated using the horizontal lines on the diagram, i.e. at a gauge pressure of 60,7 barg the strain on the outside of the pipe is measured to be approximately 0,000116 circumferentially. The longitudinal strain is approximately 0,00003.

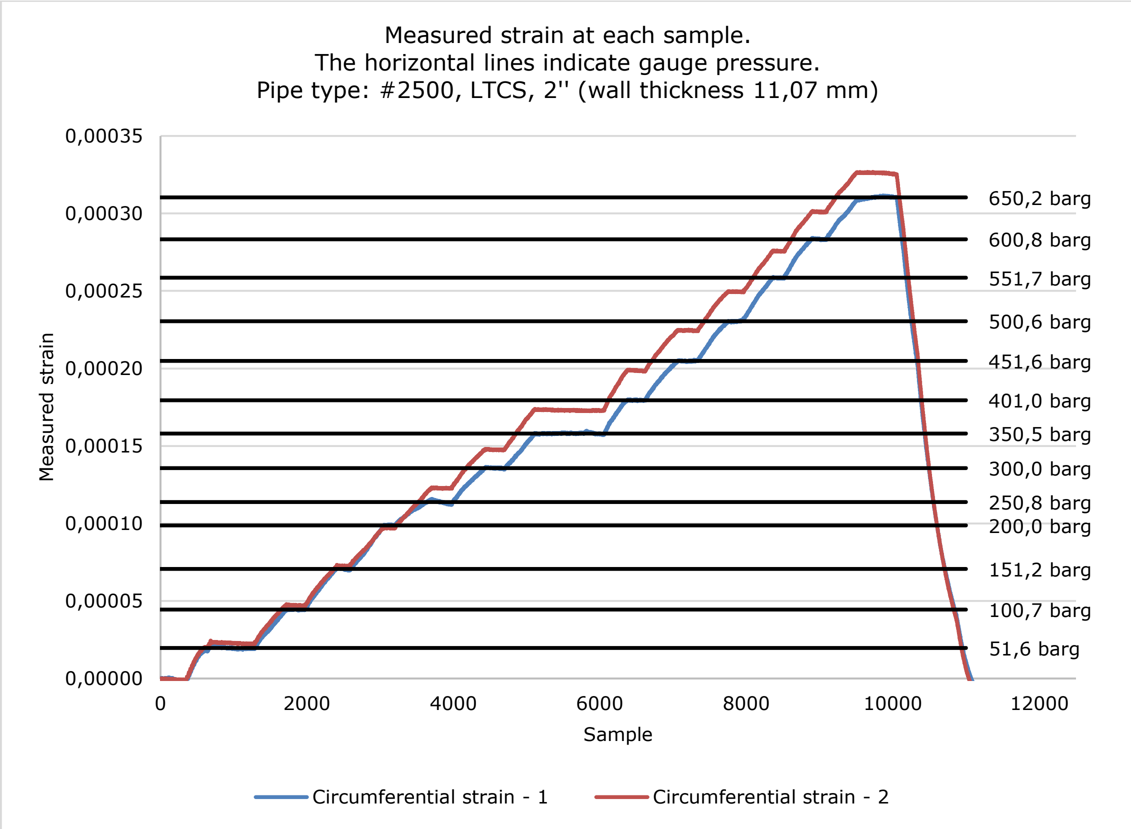

Figure 3-18: Experimental results from test 2, after the data have been processed through the simplifier

The second test was performed on a higher pound class pipe to try to mimic as close to HPHT conditions concerning pressure as possible. This test featured two different strain gauges, which both measured the circumferential strain. Circumferential strain – 1, is the same type as used in the first test, Circumferential strain – 2 is a type with the same properties with regard to gauge factor, resistance, etc., the difference is that this type does don't have a fixed wire, i.e. it has two legs where wire must be connected to by soldering. It is also twice the width, which gives a larger connection area and it should therefore give a larger strain. The gauge pressure was brought up to 650,2 barg, which lead to a measureable strain of 0,0003143 for 1 and 0,00032661 for 2.

As illustrated on Figure 3-17 and Figure 3-18 the internal pressure induces a measureable strain. The strain also develops as the gauge pressure raises.

4 Instrumentation

When a strain gauge is mounted onto a pipe is it glued to it, thus once it is attached it cannot be removed without destroying it. This section will cover a suggestion to how the instrumentation regarding the use of strain gauges can be done in a way that eases maintainability and implementation. It will also feature a description of what equipment is to be used in order to manufacture a clamp on solution which:

- Can obtain and process the strain
- Can convert strain to stress
- Can measure temperature and compensate for it
- Is easy to mount and use
- Have a display, which displays the current pressure and temperature
- Can process variable input settings such as:
  - Pipe nominal diameter
  - Piping class (material and wall thickness)
    - Wall thickness might need to be measured by ultra-sonic measurements

Figure 4-1 is a principle illustration of how the instrumentation could be done. The device consists of a small junction box mounted on a clamp with four strain gauges glued. The four strain gauges must be evenly distributed along the clamp.

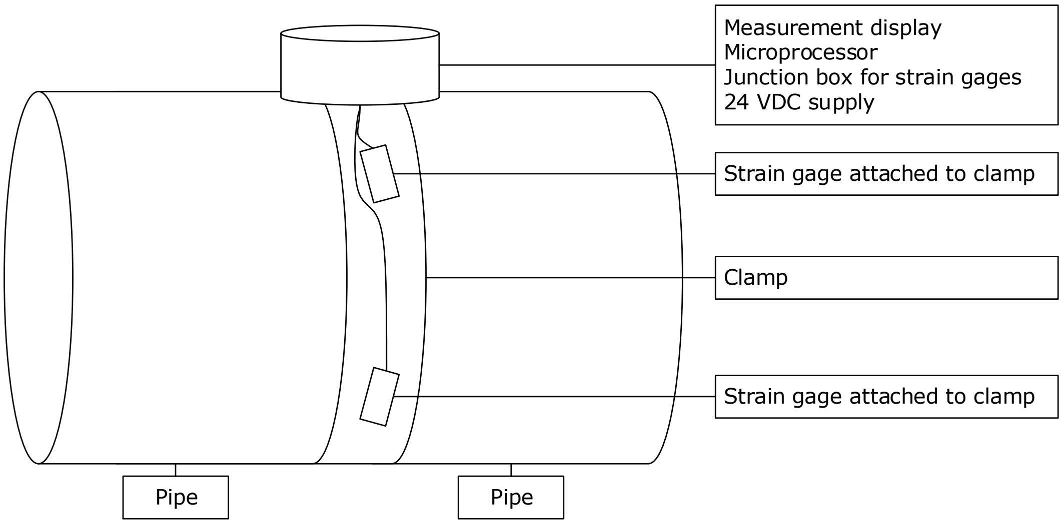

Figure 4-1: Clamp attached to pipe, with a junction box and strain gauges mounted to it

The junction box must be at least as high as the layer of insulation to have it flush or higher than the insulation layer when mounted, i.e. the height of the junction box must be at least 50 mm. It must be fitted with two PT-100 sensors. One at the bottom where the box connects tothe pipe surface to measure the temperature at the surface of the pipe and one at the top (at the top of the insulation) to measure the temperature at this point. These two temperature measurements are needed as inputs for the controller (see section 5.4).

4.1 Strain gauge

The strain gauges must be able to withstand the possible changes in temperature, i.e. a minimum temperature of -10 °C and a maximum temperature of 250 °C. This applies for the glue used to mount them to the clamp as well. Secondly, the gauge factor and resistance of the gauges must be known and stated clearly.

4.2 Clamp

The clamp must be able to fit around a pipe, i.e. it must be able to open. The facility, which is used to lock the clamp together, must be a screw, see Figure 4-2 and Figure 4-3. The clamps must be in a stainless steel material; preferably a duplex since common 316 is a very brittle material.

Figure 4-2: Clamp [11]

Figure 4-3: Clamp [12]

The clamps must have a width to accommodate the mounting width of the junction box. If this cannot be done, then three pieces must be used; one for the strain gauges and one for each side of the junction box.

4.3 Junction box

The junction box must be approved for the environment it is to be installed in, i.e. it must be ex approved in accordance with ATEX. The junction box is to be installed in zone 1, which is:

- An area in which an explosive mixture is likely to occur in normal operation

To meet this requirement the enclosure must be "Ex D".

4.4 Final instrumentation

Based on the previous subsection the final instrumentation must be able to accommodate the instruments shown in section 4.4.1, and the controller/program which is basis for the measurements must be able to process the data as shown on the flow diagram shown in section 4.4.2.

4.4.1 Simple voltage schematic

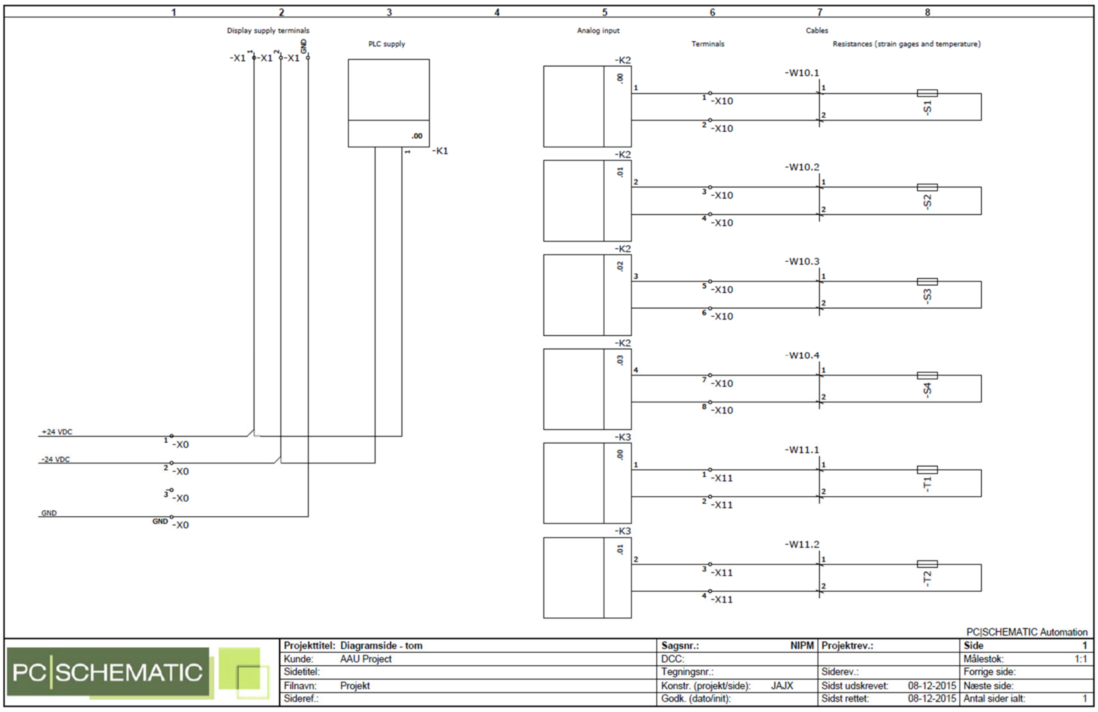

Figure 4-4: Simple schematic of the instrumentation

The PLC will be supplied with a profibus or similar to enable communication and measurement readings to be done remotely. The PLC can be a microprocessor or similar as long as it can process analogue inputs and transmit the data both locally and remotely. Locally, the data must appear on a display on the junction box. Remotely, the data must be obtained through the SCADA system.

4.4.2 Flow diagram

The controller will have the three measured inputs:

- Temperature on the pipe surface, which is the same as the inner surface temperature of the insulation.
- Temperature on the insulation surface.
- Strain on the pipe surface from the strain gauge.

Aside from these three measured inputs, there will be an operational input as well:

- Piping specification class
  - Wall thickness (thin walled hoop stress calculation or thick walled hoop stress calculation.
  - Thermal properties (thermal network and thermal strain).

The four inputs will be processed as illustrated in Figure 4-5, leading to the pressure as the single output.

The device must be able to display the three inputs measured and to transmit the data to a secondary location. There is also need for a facility to choose if the operator input shall be given locally or remotely.

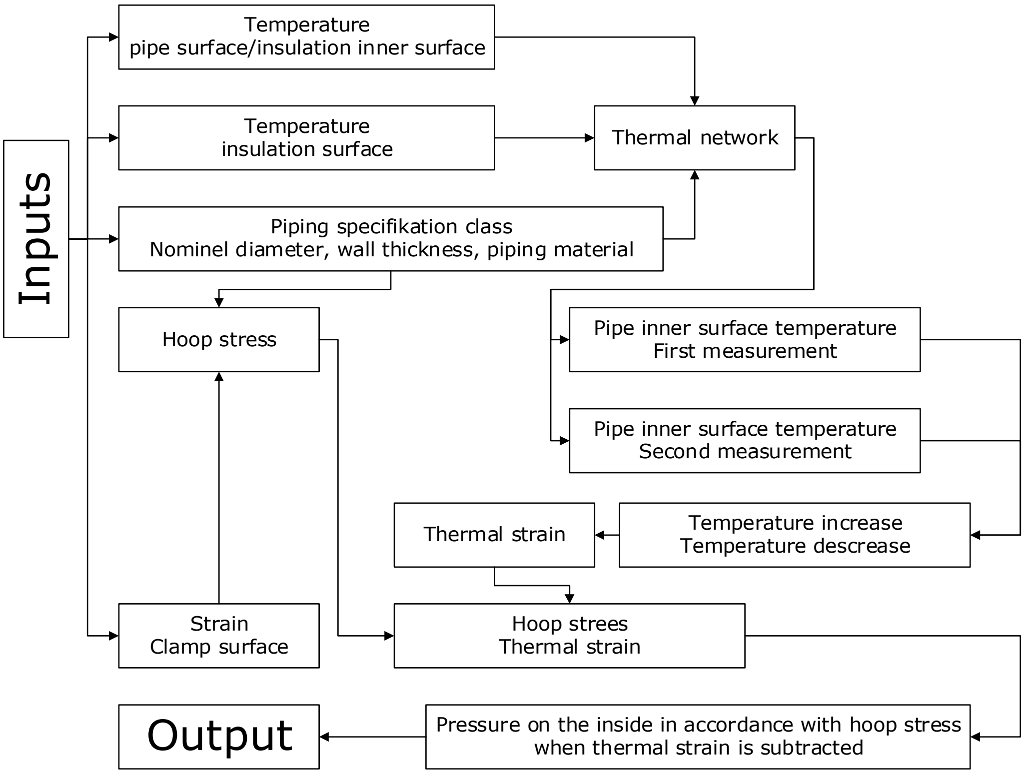

Figure 4-5: Flow diagram illustrating the process of the measurements

5 Controller

The internal pressure of a pipe induces a strain on the pipe surface which us measureable. In order to interpret this strain directly as pressure a controller is implemented. This controller must be able to compensate for the fluctuation in temperature. In order to interpret the strain as pressure one must also take into account that the pipe surface strain is not only caused by internal pressure, other things can have an influence as well such as:

- Thermal expansion longitudinal
- Thermal expansion circumferential
- Tension and torsion due to bends near measuring area
- Tension and torsion due to pipe supports.

Due to the usage of a clamp in the proposed instrumentation, it is only the circumferential thermal expansion which must be compensated for in this controller. The following sections will clarify the parts that are used in the controller.

5.1 Thermal stress

Thermal strain is caused by temperature difference from a certain time, to another time influencing the material Therefore, thermal strain for a given period in time can be calculated based on measurement of temperature and knowledge about the material concerned. In this case, measurement of temperature is done by attaching a PT-100 sensor directly to the pipe and another one to the outside of the insulation of the pipe, i.e. at the junction box. The two measures are needed to determine the energy flow from the pipe. In order to calculate the energy flow from the pipe to the surroundings, the pipe must interpreted as a thermal network with a crude oil core (fluid internal flow), steel pipe insulation, and air. Figure 5-1 illustrates the energy flow that will take place from the pipe, i.e. temperature difference from inside to the outside through the resistive layers (pipe and insulation).

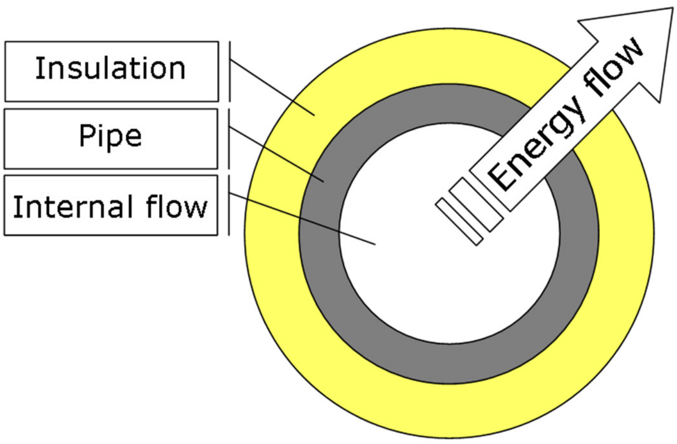

Figure 5-1: Piping thermal network

Thermal strain is calculated as follows: Firstly the thermal resistance must be determined using equation 5-1 (shown below). This is done for the insulation first. [13]

$$R_t = \frac{\ln\left(\frac{r_o}{r_i}\right)}{2 \cdot \pi \cdot L \cdot k} \qquad \text{5-1}$$

R_t is the thermal resistance through the material (at first the insulation), r_i and r_o are the radiuses (inner and outer), L is the length of the section considered and k is the thermal conductivity. [13]

Once the thermal resistance is determined, it can be used, along with the measured temperature difference from pipe surface (inner radius of insulation), to the insulation surface (outer radius of insulation), to calculate the energy which dissipates through the insulation. [13]

$$\dot{Q} = \frac{T_i - T_o}{R_t} \qquad 5\text{-}2$$

Where Q-dot is the energy flow, T_i and T_o are the measured temperatures (inside and outside). When Q-dot has been determined, it is possible to go backwards and calculate the temperature on the inner surface of the pipe assuming that no energy is lost and that the energy dissipates in one direction. [13]

The thermal stress is determined using equation 5-3 for longitudinal and 5-5 for circumferential stress. [14]

$$Thermal\ expansion\ longitudinal: \Delta L = L_0 \cdot \alpha \cdot \Delta T \qquad 5\text{-}3$$

$$L_0 = a\ considered\ length \qquad 5\text{-}4$$

$$Thermal\ expansion\ circumferential: \Delta c = (2 \cdot \pi \cdot r_0) \cdot \alpha \cdot \Delta T \qquad 5\text{-}5$$

$$c_0 = 2 \cdot \pi \cdot r_0 \qquad 5\text{-}6$$

Where L_0 is the length of the considered sample, α is the linear thermal expansion coefficient and r_0 is the considered radius. ΔT is the temperature difference between two samples, and results in the temperature increment or decrement, ΔL results in the increment or decrement in length and Δc results in the circumferential increment or decrement. Equations for determination of the three increments/decrements are shown below. [14]

$$\Delta T = T_1 - T_0 \qquad 5\text{-}7$$

$$\Delta L = L_1 - L_0 \qquad 5\text{-}8$$

$$\Delta c = c_1 - c_0 \qquad 5\text{-}9$$

Once the increments/decrements are determined they can be used to determine the stress, which is roughly a longitudinal/circumferential expansion. [14]

$$Thermal\ strain\ longitudinal: \epsilon_L = \frac{L_1 - L_0}{L_0} \qquad 5\text{-}10$$

$$Thermal\ strain\ circumferential: \epsilon_c = \frac{c_1 - c_0}{c_0} \qquad 5\text{-}11$$

The thermal strain can also be estimated by using a simpler calculation, see 5-12. The disadvantage of using this equation is that this does not account for the direction of the strain. [14]

$$\epsilon_t = \alpha \cdot \Delta T \qquad 5\text{-}12$$

It must be noted that the linear thermal expansion coefficient can be determined using equation 5-13 or looked up in a table. [14]

$$\alpha \approx \frac{0{,}020}{Melting_{point}} \qquad 5\text{-}13$$

The thermal strain can be converted to stress by using equation 5-14. This will compute the stress caused by circumferential strain due to a change in temperature. It can be done longitudinal as well by using the strain computed in that direction. [14]

$$\sigma_t = E \cdot \epsilon_c \qquad 5\text{-}14$$

The value calculated here is the value which must be compensated for in the controller, in order to neglect thermal stress as a part of the pressure measurement. [14]

5.2 Hoop stress

In order to relate the inner pressure of a pipe to a given strain or stress on the outside of the pipe one must calculate the hoop stress. The hoop stress can be determined through a free body equilibrium knowing that the hoop stress will be acting on each side in accordance with the thickness and the width of the section. This must be equal to the pressure inside the pipe, in accordance with the area in consideration. Figure 5-2 clarifies this.

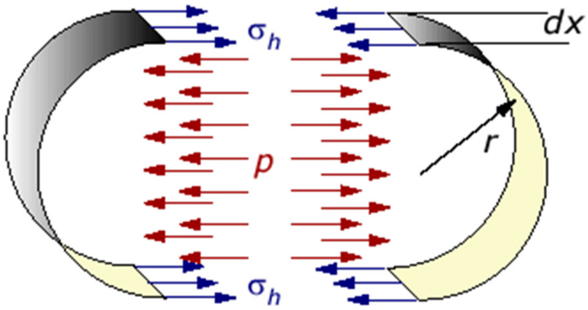

Figure 5-2: Hoop stress [8]

When Figure 5-2 and the text above is written into a formula, it results in equation 5-15. The only problem with this formula is that it only applies for thin walled pipes, i.e. the r/t (radius / wall thickness) ratio must be above 10. [8]

$$2 \cdot \sigma_h \cdot t \cdot dx = P \cdot D \cdot dx \xLeftrightarrow{rewrite\ for\ hoop\ stress} \sigma_h = \frac{P \cdot D}{2 \cdot t} = \frac{P \cdot r}{t} \qquad 5\text{-}15$$

Where σ_h is the hoop stress in MPa, t is the material thickness in mm, P is the pressure in MPa, D is the mean diameter of the pipe in mm and dx can be whatever since it reduces out. [15]

When the r/t ratio is below 10 the hoop stress is calculated using equation 5-16 and 5-17. Equation 5-16 is the same hoop stress as determined by equation 5-15. The thick walled hoop stress is higher the closer the radius in consideration is to the inner radius, is this case the hoop stress calculated will be the lowest since it is to be taken at r = r_o. The stress in the radial direction can be determined by using equation 5-17, and will the highest where r = r_o. [16]

$$\sigma_h = \frac{P_i \cdot r_i^2 - P_o \cdot r_o^2}{r_o^2 - r_i^2} - \frac{r_i^2 \cdot r_o^2 \cdot (P_o - P_i)}{r^2(r_o^2 - r_i^2)} \qquad 5\text{-}16$$

$$\sigma_r = \frac{P_i \cdot r_i^2 - P_o \cdot r_o^2}{r_o^2 - r_i^2} + \frac{r_i^2 \cdot r_o^2 \cdot (P_o - P_i)}{r^2(r_o^2 - r_i^2)} \qquad 5\text{-}17$$

The hoop stress is the same as the circumferential stress, i.e. equation 5-14, 5-15 and 5-16 determines a stress in the same direction, and can therefore be combined to determine a result, which should be the pressure. [16]

5.3 Longitudinal stress

The stress which an internal pressure induces is not only influencing on the circumference, it also causes a longitudinal stress, see Figure 5-3. This figure shows that the pressure on the inside area of the pipe must be equal to the perimeter timed with the thickness of the pipe as well as the stress caused on it. This results in equation 5-18.

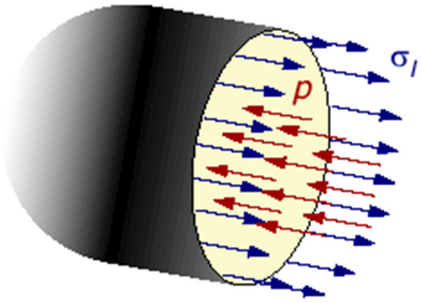

Figure 5-3: Longitudinal stress [8]

Equation 5-18 is only valid for thin-walled pipes. The same as for hoop stress applies for the longitudinal stress that leads to equation 5-19, for thick-walled pipes. [15] [16]

$$\sigma_l \cdot t \cdot 2 \cdot \pi \cdot r = P \cdot \pi \cdot r^2 \overset{\text{rewrite for longitudinal stress}}{\Longleftrightarrow} \sigma_l = \frac{P \cdot r}{2 \cdot t} = \frac{P \cdot D}{4 \cdot t} \qquad 5\text{-}18$$

$$\sigma_l = \frac{P_i \cdot r_i^2 - P_o \cdot r_o^2}{r_o^2 - r_i^2} \qquad 5\text{-}19$$

5.4 Combined controller

The formulas given in section 5.1 must be combined to one formula, which can be combined with the ones from section 5.2 in order to have a formula to be used in the controller.

$$\dot{Q} = \frac{T_{0,iso,i} - T_{0,iso,o}}{\frac{\ln\left(\frac{r_{iso,o}}{r_{iso,i}}\right)}{2 \cdot \pi \cdot L \cdot k_{iso}}} = \frac{T_{0,pipe,i} - T_{0,iso,i}}{\frac{\ln\left(\frac{r_{iso,i}}{r_{pipe,i}}\right)}{2 \cdot \pi \cdot L \cdot k_{pipe}}} \qquad 5\text{-}20$$

From here $T_{0,pipe,i}$ must be with a hold to the next sample. This is because:

$$\Delta T = T_{1,pipe,i} - T_{0,pipe,i} \qquad 5\text{-}21$$

The output of equation is then used in equation 5-22, leading to a determination of the thermal strain:

$$\epsilon_{thermal} = \frac{c_1 - c_0}{c_0} = \frac{(2 \cdot \pi \cdot r_{pipe,i}) \cdot \alpha \cdot \Delta T}{(2 \cdot \pi \cdot r_{pipe,i})} \qquad 5\text{-}22$$

This can be converted into thermal stress by using the following equation:

$$\sigma_{thermal} = E \cdot \epsilon_{thermal} \qquad 5\text{-}23$$

This stress must be subtracted from the hoop stress in order to compensate for the thermal stress, thus obtaining the stress caused by the pressure. Equation 5-16 is rewritten to obtain the pressure directly, see equation 5-26.

$$\sigma_h = \frac{P_i \cdot r_i^2 - P_o \cdot r_o^2}{r_o^2 - r_i^2} - \frac{r_i^2 \cdot r_o^2 \cdot (P_o - P_i)}{r^2 (r_o^2 - r_i^2)} = E \cdot \epsilon_{strain} \qquad 5\text{-}24$$

$$P_i = \frac{P_o \cdot r^2 \cdot r_o^2 + P_o \cdot r_i^2 \cdot r_o^2 - E \cdot r^2 \cdot r_i \cdot \epsilon_{strain} + E \cdot r^2 \cdot r_o^2 \cdot \epsilon_{strain}}{r^2 \cdot r_i^2 + r_i^2 \cdot r_o^2} \qquad 5\text{-}25$$

$$P_i = \frac{P_o \cdot r_i^2 + P_o \cdot r_o^2 - E \cdot r_i^2 \cdot \epsilon_{strain} + E \cdot r_o^2 \cdot \epsilon_{strain}}{2 \cdot r_i^2} \; (when\; r = r_o) \qquad 5\text{-}26$$

In order to obtain the pressure when temperature stress is compensated for equation 5-22 and equation 5-26 are combined as described earlier:

$$P_i = \frac{P_o \cdot r_i^2 + P_o \cdot r_o^2 + \Delta T \cdot \alpha \cdot r_i^2 - \Delta T \cdot \alpha \cdot r_o^2 - E \cdot r_i^2 \cdot \epsilon_{strain} + E \cdot r_o^2 \cdot \epsilon_{strain}}{2 \cdot r_i^2} \; (when\; r = r_o) \qquad 5\text{-}27$$

5.4.1 Simulink controller

These equations are complex to work with because they must be used in a certain order to give the correct output, i.e. the internal pressure. To ease the process, SIMULINK is used to make a controller that performs the calculations described previously. This section describes how.

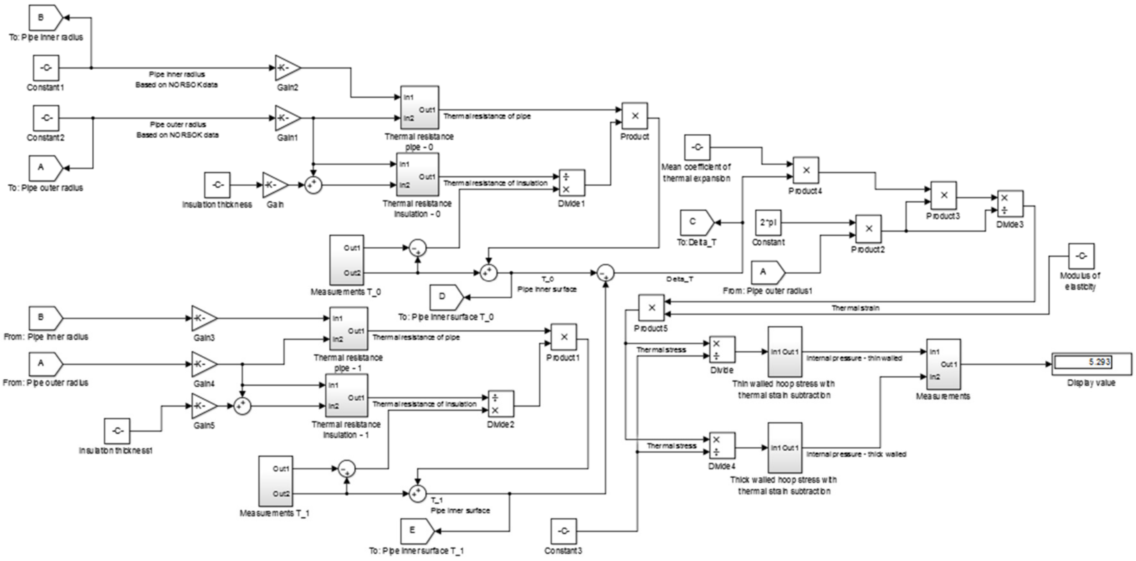

Figure 5-4: SIMULINK - Controller

Figure 5-4 shows a schematic outline of the controller which is used to determine the internal pressure. The system consists of a range of subsystems taking care of thermal resistance in insulation and pipe, temperature inputs, hoop stress for both thin and thick walled pipe respectively. All constants are determined based on one of two MATLAB scripts. The first subsystems that are encountered are the two thermal resistances. These are used to determine the temperature on the inside of the pipe, The subsystems can be seen on Figure 5-5 and Figure 5-6.

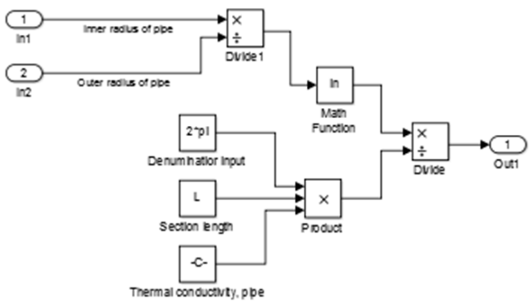

Figure 5-5: SIMULINK - Thermal resistance network pipe – 0

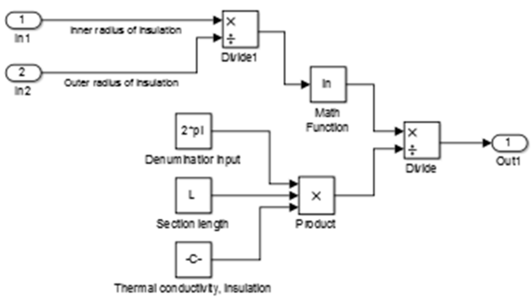

Figure 5-6: SIMULINK - Thermal resistance network insulation – 0

The inputs to these networks pipe and insulation dimensions, which are manual inputs, typed into MATLAB by the operator. The constants are found in MATLAB. In order to use the thermal networks to determine the temperature inside the pipe, a temperature input subsystem is made, see Figure 5-7.

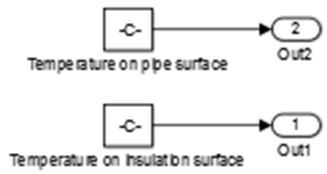

Figure 5-7: SIMULINK - Measurements T_0

These are constants for now in the present test. However, when implemented properly these must be wired to inputs as stated in section 4. The pipe dimensions also affect how the hoop stress is calculated, thin walled or thick walled. Both ways to calculate the hoop stress are implemented into the controller, see Figure 5-8 and Figure 5-9.

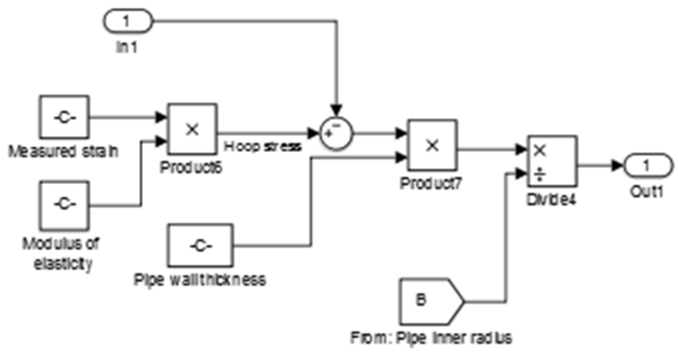

Figure 5-8: SIMULINK - Thin walled hoop stress calculation, with thermal compensation

The thin walled hoop stress calculation compensates for thermal stress. The thermal stress in the input to the calculation, and is subtracted from the mechanical stress caused by the measured strain.

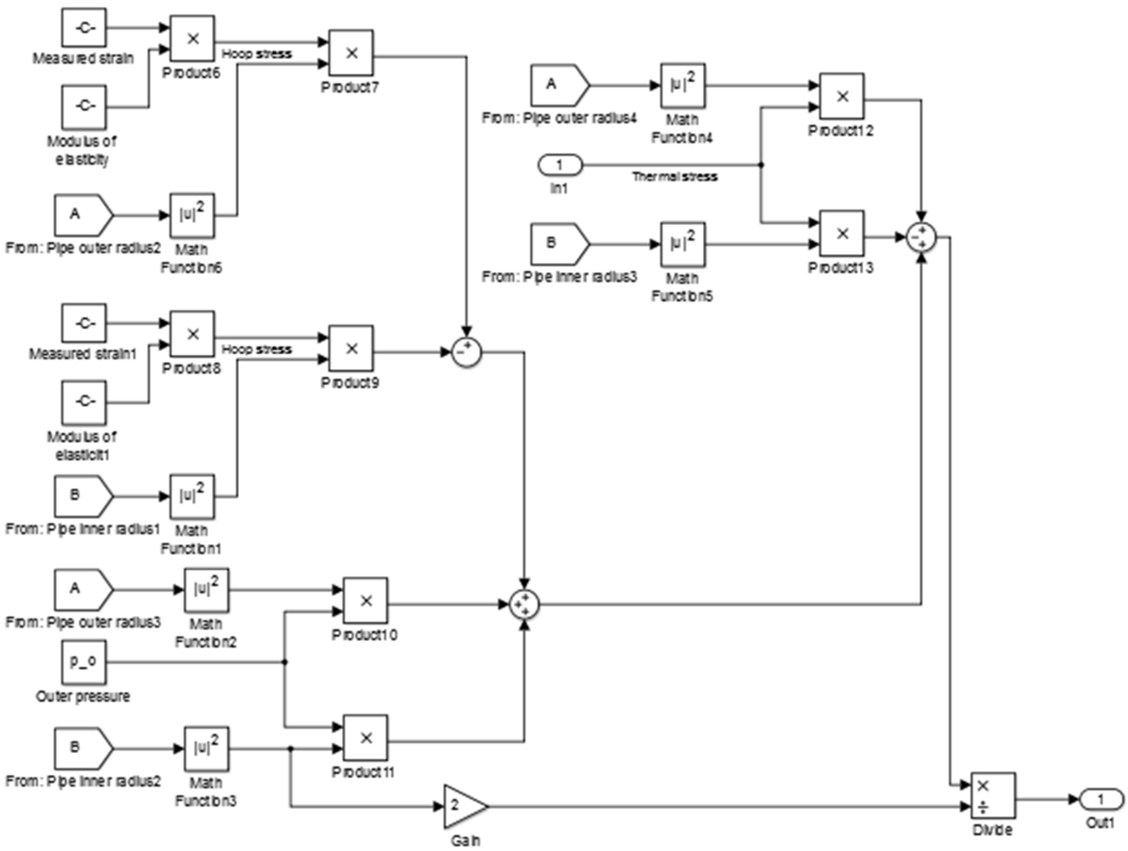

Figure 5-9: SIMULINK - Thick walled hoop stress calculation, with thermal compensation

The measurements obtained through the system are all taken into a subsystem to maintain a better outline of the system. Inside the subsystem, shown in Figure 5-10, the displays show the values which are to be obtained and transmitted to the main system. The output of the system is the actual internal pressure based on a selection matrix which determines if the pipe is thick walled or thin walled.

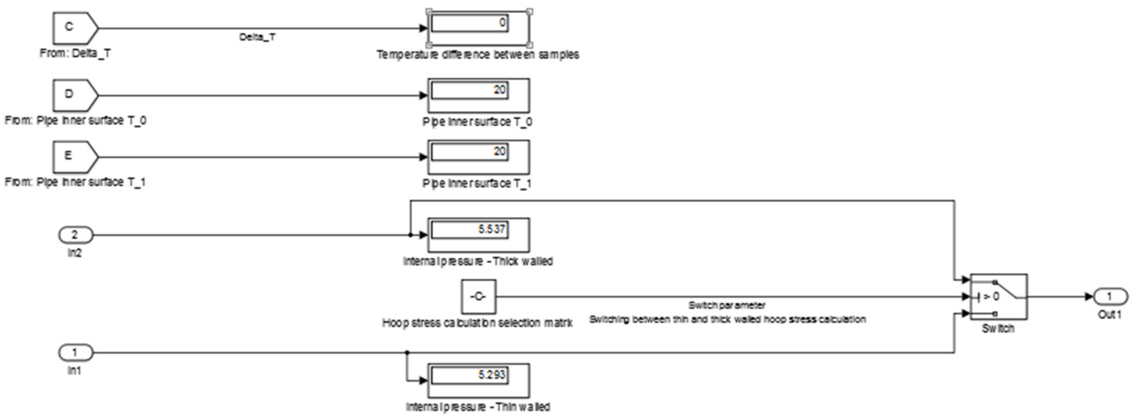

Figure 5-10: SIMULINK - Measurements

5.4.2 Using the controller with manual inputs

As described earlier, the system needs information on nominal diameter and specification class of the pipe. This information must be entered manually into the system. They are typed into MATLAB, in the file called Input.m found in Appendix 4. . If the controller is used manually, the measured inputs are typed in as well once this is done the file is run. This file also runs the other two input files, described below. Each time the input file is run; it resets the workspace and fills it again with the updated values.

The file Constants.m found in Appendix 5 determines the constants by using the equations from section 2 combined with the temperatures from the input file.

The third file NORSOK.m found in Appendix 6 gives the piping dimensions based on NORSOK piping specifications classes and the input file.

Once these parts are done, the SIMULINK file can be run. The calculated internal pressure will then change based on the strain entered in the input file. It can be monitored on the displays.

5.4.3 Using the controller with the test results as input

For each pipe, the strains obtained in the test was entered to the input file in MATLAB and the nominal diameter and piping specification class was selected in the input file. These inputs were made to match the test circumstances.

The manual inputs are:

- nominel_diameter = 7 (referring to 4")
- piping_spec = 1 (referring to AC11 – pound class #150 and material LTCS)

The difference between the temperature at T_0 and T_1 is set to zero, i.e. the two temperatures are the same. The obtained strains from the test is listed in Table 5-1 in the first column. In the second and third column, the calculated internal pressure is listed, one using thick walled hoop stress calculation and one using thin walled hoop stress calculation (the two equations are 5-15 and 5-16 respectively).

Table 5-1: Obtaiend strains on 4" AC11 pipe (pound class of #150 and LTCS material) converted to internal pressure

Measured circumferential strain	Thick walled hoop stress calculation to derive internal pressure	Thin walled hoop stress calculation to derive internal pressure
[-]	[barg]	[barg]
0,0000066402	1,7	1,6
0,0000172625	4,4	4,1
0,0000386406	9,7	9,2
0,0000485247	12,2	11,6
0,0000579474	14,6	13,8
0,0000677450	17,1	16,1
0,0000777454	19,6	18,5
0,0000887992	22,4	21,2
0,0000983990	24,8	23,4
0,0001059385	26,7	25,2
0,0001172162	29,6	27,9

Figure 5-11 displays a plot of the values shown in from Table 5-1. The plot illustrates that there is no significant difference between the two ways of determining the internal pressure for piping of this size, pound class and material. Secondly, it also clearly illustrates the linearity that is connected with both equations.

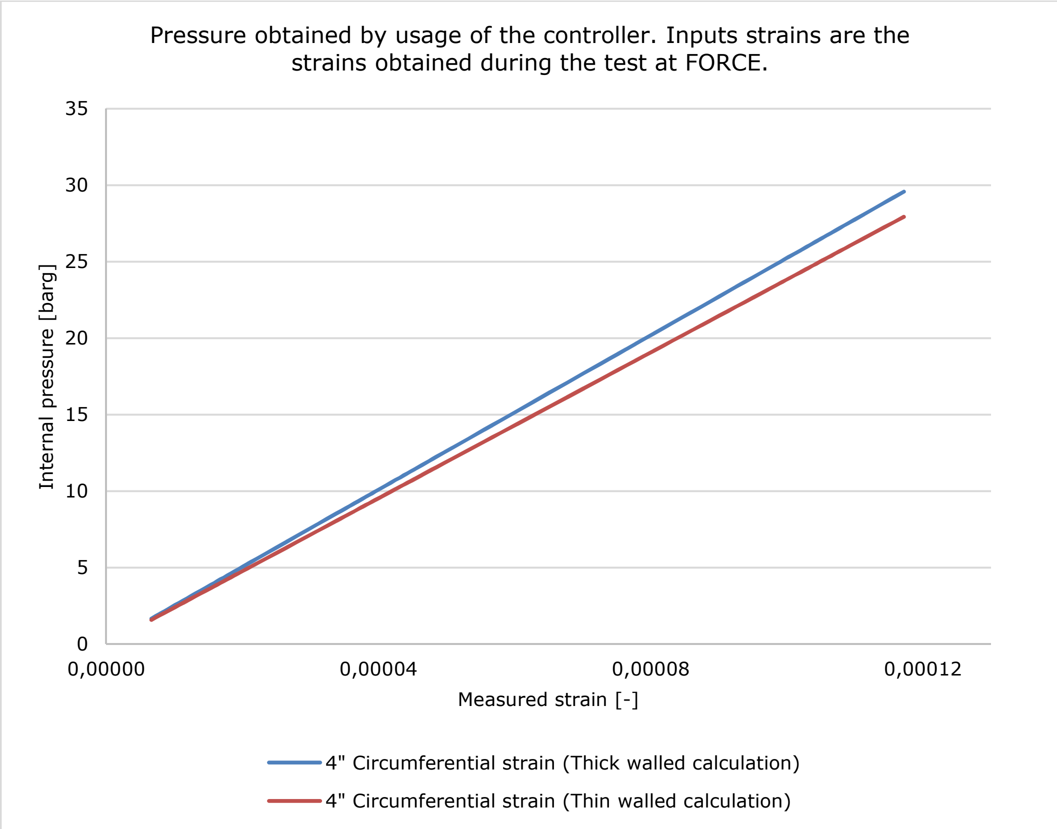

Figure 5-11: Test results from 4" #150 pipe processed through the controller

The same procedure was performed using the strains obtained through the second test. The strains and resulting pressures are listed in Table 6-2.

Table 5-2: Strains obtained on 2" GC11 pipe (pound class of #2500 and LTCS material) converted to internal pressure

Measured circumferential strain - 1	Thick walled hoop stress calculation to derive internal pressure	Thin walled hoop stress calculation to derive internal pressure
[-]	[barg]	[barg]
0,0000198478	51,7	35,8
0,0000445620	116,0	80,3
0,0000707483	184,2	127,5
0,0000988404	257,3	178,1
0,0001138478	296,4	205,1
0,0001357852	353,5	244,6
0,0001581225	411,7	284,9
0,0001795290	467,4	323,5
0,0002048648	533,4	369,1
0,0002304783	600,1	415,2
0,0002584302	672,9	465,6
0,0002833761	737,8	510,5
0,0003102172	807,7	558,9

Measured circumferential strain - 2	Thick walled hoop stress calculation to derive internal pressure	Thin walled hoop stress calculation to derive internal pressure
[-]	[barg]	[barg]
0,0000228902	59,6	41,2
0,0000472268	123,0	85,1
0,0000726169	189,1	130,8
0,0000971542	253,0	175,0
0,0001227900	319,7	221,2
0,0001475992	384,3	265,9
0,0001730587	450,6	311,8
0,0001986431	517,2	357,9
0,0002244908	584,5	404,5
0,0002494532	649,5	449,4
0,0002756125	717,6	496,6
0,0003009910	783,7	542,3
0,0003260231	848,9	587,4

Figure 5-12 illustrates the plotted data from Table 6-2. The figure shows that when the strain increases, the difference between the two ways to determine the internal pressure increases. Secondly, the linearity is once again clear (the plots from 1 and 2 are on top of each other at the respective calculations).

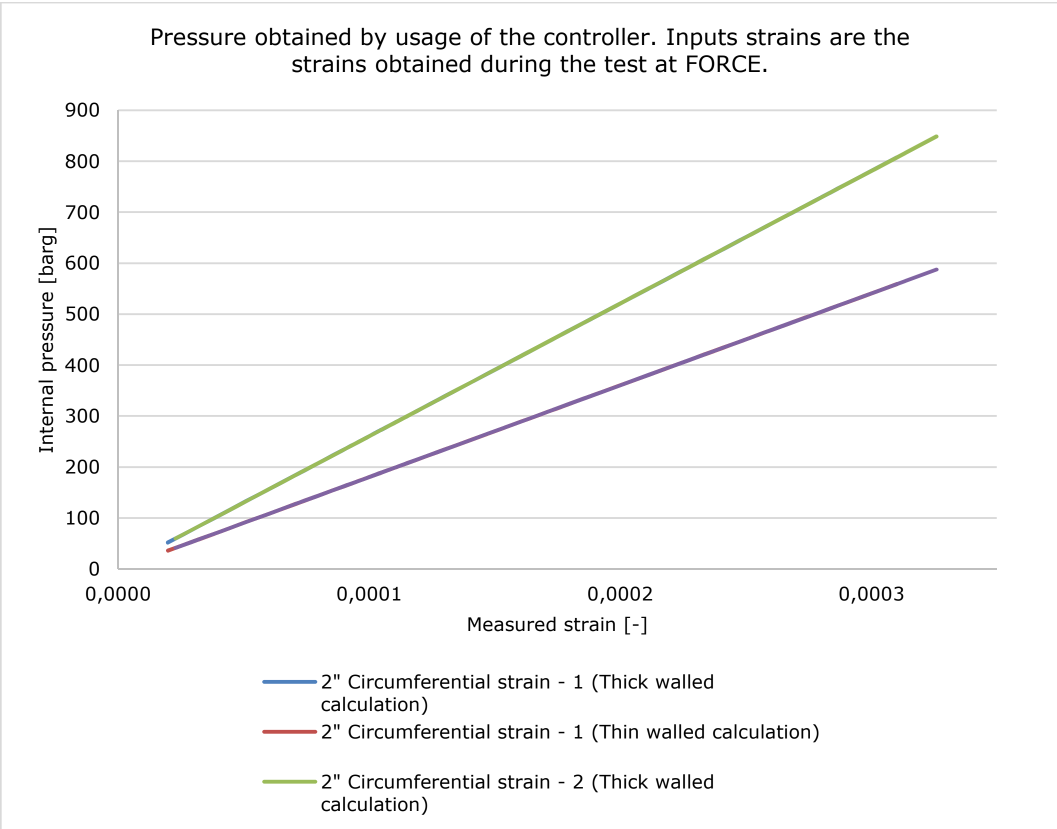

Figure 5-12: Test results from 2” #2500 pipe processed through the controller

Seeing that the strains from the test both produce linear plots the controller is functioning in accordance to the theory described in section 5.1 and 5.2.

6 Discussion and conclusion

The following subsections present a discussion of the results and a conclusion to the overall subject:

- Is it possible to make a controller that can convert measures of surface strain to internal pressure in a pipe? – So that the pressure measurement is non-invasive.

The discussion is divided into subsections matching the headers in the previous sections. Each subsection will discuss the information given in the section with regards to properties and design in relation to the progress of a future phase of this project.

6.1 Piping and materials

The equations for approximating the constants which are needed for the calculations are approximations. This introduces a minor uncertainty. This uncertainty can have a greater influence if the material composition used is not in accordance to the material composition used as a basis for the equations.

Piping dimensions used here are taken directly from NORSOK L-001. This features an uncertainty due to firstly a tolerance below the stated value of 12,5% [17]. Secondly, there is a corrosion allowance for the carbon steel piping. This will lead to thinning of the piping walls with time, i.e. the hoop stress will increase over time, not only on the basis of the internal pressure. Thirdly, the thickness is not guaranteed to be the same in any direction along the pipe, i.e. it can vary in the longitudinal direction as well as circumferential. This can be countered by measuring the wall thickness at the point where the reading must be obtained. There are two ways to do this:

- Mounting an ultra sound system that can obtain the wall thickness and provide the measure as a direct input to the controller.
- Using ultra sound to obtain the wall thickness as a manual reading at an appropriate interval and providing it as a manual input to the controller.

6.2 Testing

The results of the test at FORCE technology confirmed that when the pressure inside a pipe is increased, the strain is also increased. The results of must be considered with the following limitations:

- As stated in the previous, the wall thickness and diameter of the pipe is not necessarily the value which is stated in NORSOK.
- The temperature at the facility has been estimated to be 20 °C and the internal temperature has been assumed to be the same which is not necessarily the case. The internal pressure was read manually from a secondary location, i.e. there might be an minor pressure loos through the hose leading to the pipe.

To encounter these challenges the test should be performed using digital reading of the pressure, which can obtain the pressure reading and the strain reading simultaneously. If this is done then the results are also more comparable due to the elimination of sample dependency.

6.3 Instrumentation

Using strain gauges at the environmental temperatures associated with HPHT conditions poses a challenge concerning the strain gauge itself as well as for the adhesive used to fasten it to the clamp (or pipe). High endurance (heavy-duty) strain gauge is required. Micro Measurements [1] is one manufacturer that offers strain gauges which can operate under HPHT conditions, concerning temperature. The gauge series relevant have the following properties:

Table 6-1: Useable strain gauges [1]

Gauge series	Temperature range	Strain level $[\varepsilon^{-6}]$	Number of cycles
WA	Normal: -75 °C to 205 °C Short term: -195 °C to 230 °C	± 2000 ± 1800 ± 1500	10^5 10^6 10^7
SA	Normal: -75 °C to 205 °C Short term: -195 °C to 230 °C	± 1800 ± 1500	10^6 10^7
WD	Dynamic: -195 °C to 260 °C	± 3000 ± 2500 ± 2200	10^6 10^7 10^8
WK	Normal: -269 °C to 290 °C Short term: -269 °C to 400 °C	± 2200 ± 2000	10^6 10^7
SK	Normal: -269 °C to 230 °C Short term: -269 °C to 260 °C	± 2200 ± 2000	10^6 10^7

If the strain gauge is to operate at HPHT conditions, the strains obtained must relate to a maximum pressure of 1380 barg. The piping specifications classes referred to in NORSOK relate to lower pressures, i.e.:

Table 6-2: Pound class equivalent pressures in barg

Pound class	#150	#300	#600	#900	#1500	#2500
Pressure[barg]	20	50	100	150	250	420

Using the strain levels from Table 6-2 it can be determined if any of the useable strain gauges, in relation to temperature, are unusable due to the strain level. The strain levels are inserted into the controller to obtain the internal pressure, which can be obtained at these strains.

Strain level	Minimum pressure obtained at maximum strain level	Maximum pressure obtained at maximum strain level
0,0015	64,54	15505,85
0,0018	77,45	18607,02
0,0020	86,06	20674,47
0,0022	94,66	22741,91
0,0025	107,57	25843,08
0,0030	129,09	31011,70

When the strain levels are taken in conjunction with the temperature levels, the gauge series WD seems to be the most appropriate for the task, although further testing must be conducted to verify the strain region of the strain gauge.

6.3.1 Adhesive for fastening onto clamp

Besides the strain gauges, the adhesive used to fasten it is also a concern, to comply with the same temperatures as before an adhesive from Tokyo Sokki Kenkyujo [18] can be used. They produce a type that can operate within a temperature range of -269 °C to 300 °C.

6.3.2 Junction box

The temperature conditions on and around the pipe poses a challenge with regards to the junction box if it is to be mounted on the pipe, due to the material of the most common Ex-d junction boxes being made of plastic or a type of metal. In either case, the box must be insulated from the pipe to avoid heat dissipating to the box and destroying components inside the junction box. A way to counter this challenge is to mount the junction box at a secondary location, i.e. supplying the strain gauge and temperature gauges with 1-2 meters of cable to enable a possibility of mounted the box away from the measuring location.

6.4 Controller

In order to accommodate the improvement suggestions from section 6.1, the controller must be able to handle additional inputs:

- Wall thickness from ultra sound
- Diameter/radius from ultra sound

These two inputs can also be obtained through manual inputs, i.e. as a measurement at a certain interval and then used to update the pipe dimensions matrixes already in the controller.

Additionally, the compensation in relation to thermal stress can be made more accurate using hold functions on dimensions concerning increase/decrease of radius. For the suggested controller, the radius is always taken as a relation between a state before the first measurement and the first measurement, i.e. T_0 and T_1. With a hold function the controller will be able to take a delta measurement between all steps, i.e. T_0-T_1, T_1-T_2, T_2-T_3, etc. This delta will also apply for the temperature measurements obtained through the controller.

6.5 Overall discussion and conclusion

This subsection sums up the previous sections points, as well as a comparison of the test results and the results using the controller.

6.5.1 Controller accuracy

Figure 5-11 illustrates the controller results obtained on the 2” pipe, i.e. test 1. Figure 6-1 shows these results along with the results from the test at FORCE TECHONOLOGY.

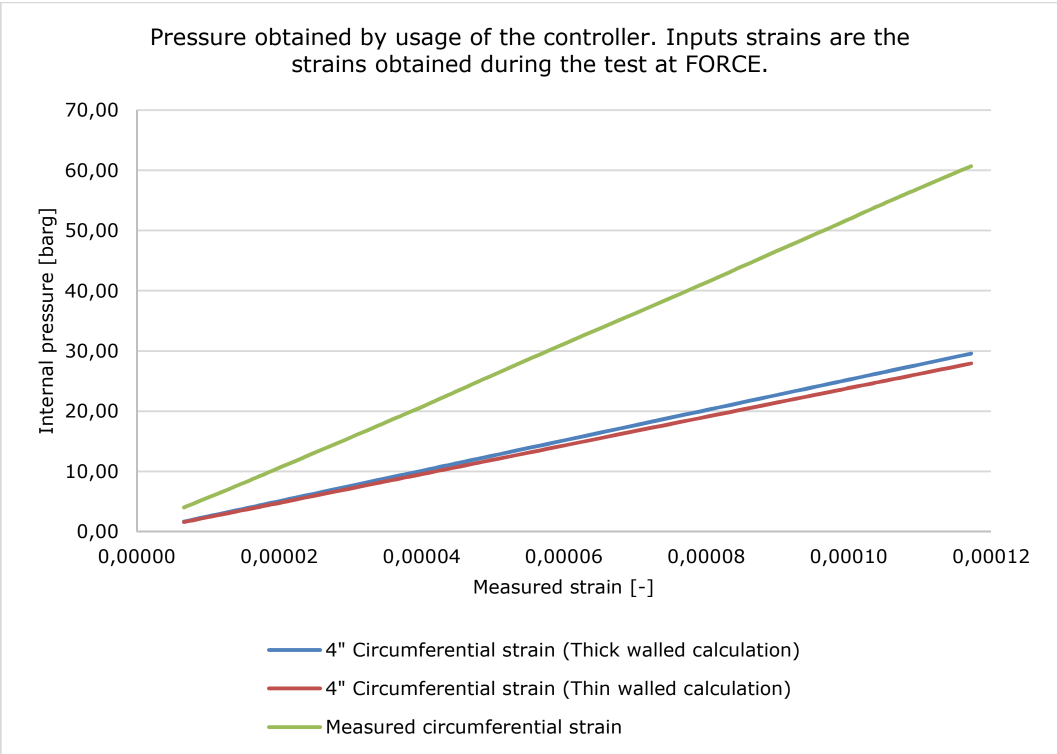

Figure 6-1: Controller pressure and measured pressure (obtained during test 1)

The figure illustrates that the test results obtained are different from the results obtained through the controller, i.e. theoretical. The difference between the test results and the theoretical results is approximately a factor 2. At the highest obtained strain the gauge pressure at FORCE was 60 barg, but when using the controller the pressure obtained is only 30 barg.

Figure 6-2 illustrates the test results from the second test and the value obtained using the controller. The values represented on this figure are a closer match than the previous.

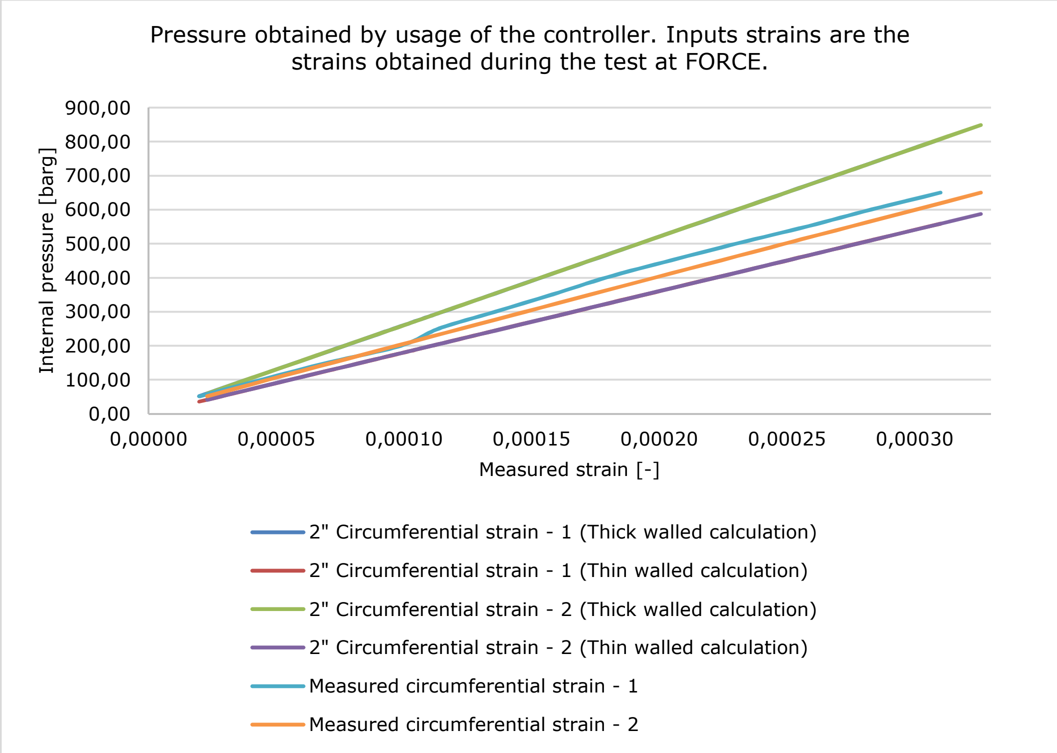

Figure 6-2: Controller pressure and measured pressure (obtained during test 2)

The difference between the test results and the theoretical results are different here, than the results from test 1. The test results are between the thin walled and thick walled calculation. This can also be seen from Figure 6-3, where the "error" from test 1 is also represented. A relative error of 0 % indicates that the test results and the theoretical results match 100 %.

There are things which will cause an error that are not taken into account during the test:

- When shaping metal, the process can cause the top layer (up to 1 mm) to have a different elasticity than the rest of the metal, i.e. the surface can be harder or softer thus giving a smaller or larger strain than what is cause by the internal pressure. This might be valid explanation for the error in test 1.
- The gauge pressure during the test was a manual read off. It would be preferred to have it obtained through the same device as the strain, e.g. a computer using LABVIEW. If this is done, the two graphs can be compared step by step. It will also enable a possibility to determine the delay of the system, thus giving an indication on whether a PID (or similar) controller is needed to improve the theoretical determined pressure.
- The "error" during the two test is inconsistent thus more testing is needed to determine if a strain gauge can be used, or if it is to inaccurate.

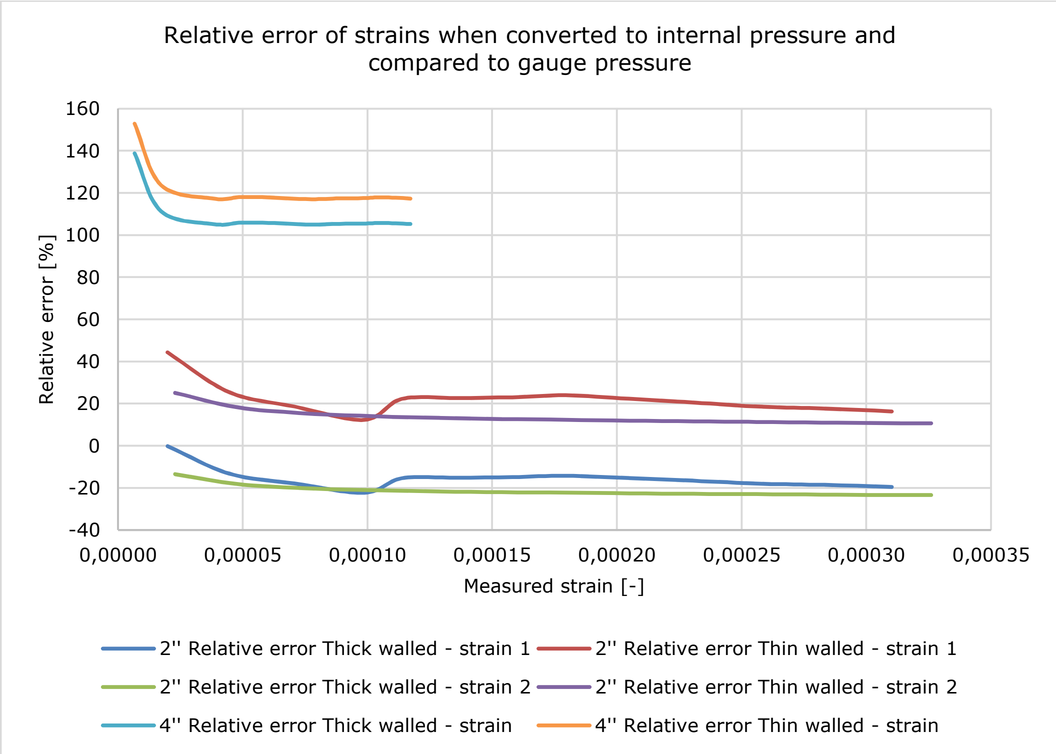

Figure 6-3: Plot of the relative error between the obtained measurements and the theoretically obtained internal pressure

6.5.2 Maintainability

The maintenance costs for the product are low. The strain gauges are mounted onto a clamp, where the temperature sensors are also located. When a sensor does not read off as it is supposed to, the entire clamp must changed to a new one. The only thing that is needed to perform this process is to dismount the sensors from the junction box and then dismount the clamp form the pipe.

6.5.3 Conclusion

Using strain gauges to obtain the surface strain directly on the pipe was possible and the read off changed in accordance with the change in gauge pressure.

Further testing must be done, in relation to the controller accuracy. The tests must also be conducted on pipes with surface treatment because the surface treatment will have different thermal and mechanical properties. The tests must be done using a clamp on solution to determine if the expansion force performed by the internal pressure can be transferred from the pipe through a surface treatment onto a metal clamp.

In relation to the feasibility of transference of an internal pressure through a pipe, it is possible using hoop stress calculations although the accuracy is off, i.e. further testing is needed.

7 Bibliography

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Appendix 1 Pipe standard/grade

Piping specification class	Pound class	Material	Range	Standard/grade
AC11	#150	LTCS	0,5-24″	A333, Grade 6, SMLS
			8-36″	A671, CC60
BC11	#300	LTCS	0,5-24″	A333, Grade 6
			8-36″	A671, CC60
DC11	#600	LTCS	0,5-24″	A333, Grade 6
			8-36″	A671, CC70, CL22
EC11	#900	LTCS	0,5-16″	A333, Grade 6, SMLS
			18-24″	API 5L GrX52
FC11	#1500	LTCS	0,5-6″	A333, Grade 6, SMLS
			8-24″	API 5L GrX52
GC11	#2500	LTCS	0,5-6″	A333, Grade 6, SMLS
			8-24″	API 5L GrX52
AS20	#150	Stainless Steel	0,5-8″	A312, TP316, SMLS
			1-30″	A358, 316 CL5
BS20	#300	Stainless Steel	0,5-6″	A312, TP316, SMLS
			6-36″	A358, 316 CL1, 3 OR 4
DS20	#600	Stainless Steel	0,5-24″	A312, TP316, SMLS
			3-24″	A358, 316 CL1, 3 OR 4
ES20	#900	Stainless Steel	0,5-24″	A312, TP316, SMLS
			4-24″	A358, 316 CL1, 3 OR 4
FS20	#1500	Stainless Steel	0,5-24″	A312, TP316, SMLS
			8-24″	A358, 316 CL1, 3 OR 4
GS20	#2500	Stainless Steel	0,5-12″	A312, TP316, SMLS
			8-12″	A358, 316 CL1, 3 OR 4
AD20	#150	Duplex (22 Cr)	0,5-8″	A790, S31803, SMLS
			1-30″	A928, S31803 CL5
BD20	#300	Duplex (22 Cr)	0,5-6″	A790, S31803, SMLS
			1-10″	A928, S31803 CL5
			12-24″	A928, S31803 CL1 OR 3
DD20	#600	Duplex (22 Cr)	0,5-16″	A790, S31803, SMLS
			4-24″	A928, S31803 CL1 OR 3
ED20	#900	Duplex (22 Cr)	0,5-18″	A790, S31803, SMLS
			4-24″	A928, S31803 CL1 OR 3
FD20	#1500	Duplex (22 Cr)	0,5-14″	A790, S31803, SMLS
			8-24″	A928, S31803 CL1 OR 3
GD20	#2500	Duplex (22 Cr)	0,5-14″	A790, S31803, SMLS
			8-24″	A928, S31803 CL1 OR 3
AD30	#150	Super Duplex (25 Cr)	0,5-8″	A790, S32750
			1-30″	A928, S32750 CL1 OR 3
BD30	#300	Super Duplex (25 Cr)	0,5-8″	A790, S32750, SMLS
			1-36″	A928, S32750 CL1 OR 3
DD30	#600	Super Duplex (25 Cr)	0,5-14″	A790, S32750, SMLS
			4-24″	A928, S32750 CL1 OR 3
ED30	#900	Super Duplex (25 Cr)	0,5-14″	A790, S32750, SMLS
			4-24″	A928, S32750 CL1 OR 3
FD30	#1500	Super Duplex (25 Cr)	0,5-14″	A790, S32750, SMLS
			8-24″	A928, S32750 CL1 OR 3
GD30	#2500	Super Duplex (25 Cr)	0,5-14	A790, S32750, SMLS
			1-24″	A928, S32750 CL1 OR 3

Appendix 2 Pipe wall thickness

	Piping specification class	All pipe wall thicknesses in [mm] based on NORSOK piping specification class.															
Piping nominal diameter		0,5''	0,75''	1''	1,5''	2''	3''	4''	6''	8''	10''	12''	14''	16''	18''	20''	24''
	AC11	4,78	5,56	6,35	5,08	5,54	5,49	6,02	7,11	6,35	6,35	6,35	7,92	7,92	7,92	9,53	9,53
	BC11	4,78	5,56	6,35	5,08	5,54	5,49	6,02	7,11	8,18	9,27	10,31	11,13	12,70	14,27	15,09	17,48
	DC11	4,78	5,56	6,35	7,14	8,74	7,62	8,56	10,97	12,70	15,09	17,48	19,05	21,44	23,83	26,19	30,96
	EC11	4,78	5,56	6,35	7,14	8,74	11,13	11,13	14,27	18,26	21,44	25,40	27,79	30,96	29,36	32,54	38,89
	FC11	7,47	7,82	9,09	10,15	11,07	15,24	17,12	21,95	25,00	28,58	33,32	35,71	40,49	45,24	50,01	59,54
	GC11	7,47	7,82	9,09	12,50	14,20	17,50	22,20	30,00	36,00	45,00	50,00	55,00	65,00	70,00	80,00	95,00
	AS20	2,77	2,87	3,38	3,68	2,77	3,05	3,05	3,40	3,76	4,19	4,57	4,78	4,78	4,78	5,54	6,35
	BS20	2,77	2,87	3,38	3,68	2,77	3,05	3,05	7,11	6,35	6,35	8,38	7,92	9,53	9,53	12,70	12,70
	DS20	2,77	2,87	3,38	3,68	3,91	5,49	6,02	7,11	10,31	12,70	14,27	15,09	16,66	19,05	20,62	24,61
	ES20	3,73	3,91	4,55	5,08	5,54	7,62	8,56	10,97	15,09	18,26	21,44	23,83	26,19	29,36	32,54	38,89
	FS20	3,73	3,91	4,55	5,08	8,74	11,13	13,49	18,26	23,01	28,58	33,32	35,71	40,49	45,24	50,01	59,54
	GS20	4,78	5,56	6,35	10,15	11,07	15,24	17,50	28,00	36,00	45,00	50,00					
	AD20	2,77	2,87	3,38	3,68	2,77	3,05	3,05	3,40	3,76	4,19	4,57	4,78	4,78	4,78	5,54	6,35
	BD20	2,77	2,87	3,38	3,68	2,77	3,05	3,05	3,40	3,76	6,35	6,35	6,35	6,35	7,92	9,53	9,53
	DD20	2,77	2,87	3,38	3,68	3,91	5,49	6,02	7,11	8,18	9,27	9,53	11,13	12,70	12,70	12,70	17,48
	ED20	2,77	2,87	3,38	3,68	3,91	5,49	6,02	7,11	10,31	12,70	14,27	15,09	16,66	19,05	20,62	24,61
	FD20	2,77	2,87	3,38	3,68	5,54	7,62	8,56	14,27	18,26	21,44	25,40	27,79	26,19	29,36	32,54	38,89
	GD20	3,73	3,91	4,55	7,14	8,74	11,13	13,49	21,95	25,00	32,00	36,00	40,00	40,49	45,24	50,01	59,54
	AD30	2,77	2,87	3,38	3,68	2,77	3,05	3,05	3,40	3,76	4,19	4,57	4,78	4,78	4,78	5,54	6,35
	BD30	2,77	2,87	3,38	3,68	2,77	3,05	3,05	3,40	3,76	4,19	4,57	4,78	6,35	6,35	9,53	9,53
	DD30	2,77	2,87	3,38	3,68	2,77	3,05	3,05	7,11	6,35	7,80	8,38	9,53	9,53	9,53	12,70	14,27
	ED30	2,77	2,87	3,38	3,68	3,91	5,49	6,02	7,11	10,31	12,70	14,27	15,09	12,70	14,27	20,62	24,61
	FD30	2,77	2,87	3,38	3,68	3,91	5,49	8,56	10,97	15,09	18,26	21,44	23,83	21,44	23,83	26,19	30,96
	GD30	3,73	3,91	4,55	5,08	8,74	11,13	13,49	18,26	23,01	28,58	33,32	35,71	36,53	39,67	44,45	52,37

Appendix 3 Material properties

A333, grade 6 (LTCS)
UNS: K03006 (Material no. 1.0456)

Density [kg/m³]	Temperature [°C]	Modulus of elasticity [GPa]	Temperature [°C]	Mean coefficient of thermal expansion [10⁻⁶ °C]	Thermal conductivity [W/m·°C]	Temperature [C]	Specific thermal capacity [J/kg·°C]
7750,0	-200,0	216,0	20,0	11,5	60,4	-100,0	371,0
	-125,0	212,0	50,0	11,8	59,8	0,0	451,0
	-75,0	209,0	75,0	11,9	58,9	20,0	461,0
	25,0	202,0	100,0	12,1	58,0	100,0	496,0
	100,0	198,0	125,0	12,3	57,0	200,0	533,0
	150,0	195,0	150,0	12,4	55,9	300,0	568,0
	200,0	192,0	175,0	12,6	54,7	400,0	611,0
	250,0	189,0	200,0	12,7	53,6	500,0	677,0
	300,0	185,0	225,0	12,9	52,5	600,0	778,0
	350,0	179,0	250,0	13,0	51,4		
	400,0	171,0	275,0	13,2	50,3		
	450,0	162,0	300,0	13,3	49,2		
	500,0	151,0	325,0	13,4	48,1		
	550,0	137,0	350,0	13,6	47,0		
			375,0	13,7	45,9		
			400,0	13,8	44,9		
			425,0	14,0	43,8		
			450,0	14,1	42,7		
			475,0	14,2	41,6		
			500,0	14,4	40,5		
			525,0	14,5	39,3		
			550,0	14,6	38,2		
			575,0	14,7	37,0		
			600,0	14,8	35,8		
			625,0	14,9	34,7		
			650,0	15,0	33,5		
			675,0	15,1	32,3		
			700,0	15,1	31,2		
			725,0	15,2	30,1		
			750,0	15,3	29,1		
			775,0	15,3			
			800,0	15,4			
			825,0	15,5			

A312, TP316 (SS)
UNS: S31600 (Material no. 1.4401)

Density [kg/m³]	Temperature [°C]	Modulus of elasticity [GPa]	Temperature [°C]	Mean coefficient of thermal expansion [10⁻⁶ °C]	Thermal conductivity [W/m·°C]	Temperature [°C]	Specific thermal capacity [J/kg·°C]
8030,0	-200,0	209,0	20,0	15,3	14,1	-157,0	330,8
	-125,0	204,0	50,0	15,6	14,6	-129,0	355,9
	-75,0	201,0	75,0	15,9	15,0	-73,0	393,6
	25,0	195,0	100,0	16,2	15,4	20,0	452,2
	100,0	189,0	125,0	16,4	15,7	93,0	485,7
	150,0	186,0	150,0	16,6	16,1	204,0	527,5
	200,0	183,0	175,0	16,8	16,5	316,0	548,5
	250,0	179,0	200,0	17,0	16,8	427,0	565,2
	300,0	176,0	225,0	17,2	17,2	538,0	573,6
	350,0	172,0	250,0	17,4	17,6	649,0	586,2
	400,0	169,0	275,0	17,5	17,9	760,0	615,5
	500,0	160,0	300,0	17,7	18,3	871,0	649,0
	550,0	156,0	325,0	17,8	18,7		
	600,0	151,0	350,0	17,9	19,0		
	650,0	146,0	375,0	18,0	19,4		
	700,0	140,0	400,0	18,1	19,7		
			425,0	18,2	20,1		
			450,0	18,3	20,5		
			475,0	18,4	20,8		
			500,0	18,4	21,2		
			525,0	18,5	21,5		
			550,0	18,6	21,9		
			575,0	18,7	22,2		
			600,0	18,8	22,6		
			625,0	18,9	22,9		
			650,0	19,0	23,2		
			675,0	19,1	23,6		
			700,0	19,2	23,9		
			725,0	19,3	24,2		
			750,0	19,4	24,6		
			775,0	19,4			
			800,0	19,4			
			825,0	19,4			

A790/A928, S31803 (duplex 22 Cr)
UNS: S31803 (Material no. 1.4462)

Density [kg/m³]	Temperature [°C]	Modulus of elasticity [GPa]	Temperature [°C]	Mean coefficient of thermal expansion [10^{-6} °C]	Thermal conductivity [W/m·°C]	Temperature [C]	Specific thermal capacity [J/kg·°C]
8030,0	-200,0	214,0	20,0	12,6	14,1	20,0	480,0
	-125,0	210,0	50,0	12,8	14,6	100,0	500,0
	-75,0	207,0	75,0	13,0	15,0	200,0	530,0
	25,0	200,0	100,0	13,1	15,4	300,0	550,0
	100,0	196,0	125,0	13,2	15,7	400,0	590,0
	150,0	193,0	150,0	13,4	16,1		
	200,0	190,0	175,0	13,5	16,5		
	250,0	187,0	200,0	13,6	16,8		
	300,0	183,0	225,0	13,7	17,2		
	350,0	177,0	250,0	13,8	17,6		
	400,0	170,0	275,0	13,9	17,9		
	450,0	160,0	300,0	14,0	18,3		
	500,0	149,0	325,0	14,1	18,7		
	550,0	135,0	350,0	14,2	19,0		
	600,0	121,0	375,0	14,3	19,4		
			400,0	14,4	19,7		
			425,0	14,5	20,1		
			450,0	14,6	20,5		
			475,0	14,6	20,8		
			500,0	14,7	21,2		
			525,0	14,8	21,5		
			550,0	14,8	21,9		
			575,0	14,9	22,2		
			600,0	15,0	22,6		
			625,0	15,0	22,9		
			650,0	15,1	23,2		
			675,0	15,1	23,6		
			700,0	15,2	23,9		
			725,0	15,2	24,2		
			750,0	15,3	24,6		
			775,0	15,3			
			800,0	15,3			
			825,0	15,3			

A790/A928, S32750 (super duplex 25 Cr) UNS S32750 (Material no. 2.4660)							
Density [kg/m^3]	Temperature [°C]	Modulus of elasticity [GPa]	Temperature [°C]	Mean coefficient of thermal expansion [10^{-6} °C]	Thermal conductivity [W/m·°C]	Temperature [°C]	Specific thermal capacity [J/kg·°C]
8030,0	-200,0	214,0	20,0	12,6	14,1	20,0	480,0
	-125,0	210,0	50,0	12,8	14,6	100,0	500,0
	-75,0	207,0	75,0	13,0	15,0	200,0	530,0
	25,0	200,0	100,0	13,1	15,4	300,0	550,0
	100,0	196,0	125,0	13,2	15,7	400,0	580,0
	150,0	193,0	150,0	13,4	16,1		
	200,0	190,0	175,0	13,5	16,5		
	250,0	187,0	200,0	13,6	16,8		
	300,0	183,0	225,0	13,7	17,2		
	350,0	177,0	250,0	13,8	17,6		
	400,0	170,0	275,0	13,9	17,9		
	450,0	160,0	300,0	14,0	18,3		
	500,0	149,0	325,0	14,1	18,7		
	550,0	135,0	350,0	14,2	19,0		
	600,0	121,0	375,0	14,3	19,4		
			400,0	14,4	19,7		
			425,0	14,5	20,1		
			450,0	14,6	20,5		
			475,0	14,6	20,8		
			500,0	14,7	21,2		
			525,0	14,8	21,5		
			550,0	14,8	21,9		
			575,0	14,9	22,2		
			600,0	15,0	22,6		
			625,0	15,0	22,9		
			650,0	15,1	23,2		
			675,0	15,1	23,6		
			700,0	15,2	23,9		
			725,0	15,2	24,2		
			750,0	15,3	24,6		
			775,0	15,3			
			800,0	15,3			
			825,0	15,3			

Appendix 4 Input file (Input.m)

```
close all
clear all
clc

%   Set coefficients:

k_insulation=0.03;  %Thermal conductivity of polyurethane foam [W/m C]
t_insulation=50;    %Thickness of insulation layer [mm]
L=0.01;             %Length in consideration [m]
p_o=0;              %Outside pressure [Pa]

%%  Selections / manual inputs:

%   Nominel diameter is taken in relation to:
%   1 = 1/2"    2 = 3/4"    3 = 1"      4 = 1 1/2"      5 = 2"      6 = 3"
%   7 = 4"      8 = 6"      9 = 8"      10 = 10"        11 = 12"    12 = 14"
%   13 = 16"    14 = 18"    15 = 18"    16 = 20"        17 = 24"
nominel_diameter = 7;

%   Piping sepcification classes:
%   1 = AC11    2 = BC11    3 = DC11    4 = EC11    5 = FC11    6 = GC11
%   7 = AS20    8 = BS20    9 = DS20    10 = ES20   11 = FS20   12 = GS20
%   13 = AD20   14 = BD20   15 = DD20   16 = ED20   17 = FD20   18 = GD20
%   19 = AD30   20 = BD30   21 = DD30   22 = ED30   23 = FD30   24 = FD30
piping_spec = 1;

%   Based on piping spec the material is selected:

if piping_spec<=6;
    material = 1;
elseif 6 < piping_spec && piping_spec <= 12;
    material = 2;
elseif 13 < piping_spec && piping_spec <= 18;
    material = 3;
else 18 < piping_spec;
    material = 4;
end

%%  Direct inputs:
T_0_pipe_surface=20;       %1st measurement: Pipe surface temperature / Insulation inner surface
temperature
T_0_insulation_surface=20;  %1st measurement: Insulation surface temperature
T_1_pipe_surface=150;       %2nd measurement: Pipe surface temperature / Insulation inner surface
temperature
T_1_insulation_surface=21;  %2nd measurement: Insulation surface temperature

epsilon_pipe=0.000105938498459375;       %Measured strain

run('Constants')
run('NORSOK')
```

Appendix 5 Determine constant (Constants.m)

```
%   Determing coefficients at T_0

%   Specific thermal capacity:
c_K03006_0=-2E-14*T_0_pipe_surface^6+4E-11*T_0_pipe_surface^5-2E-8*T_0_pipe_surface^4+7E-
6*T_0_pipe_surface^3-0.0015*T_0_pipe_surface^2+0.549*T_0_pipe_surface+450.79;
c_S31600_0=-2E-15*T_0_pipe_surface^6+4E-12*T_0_pipe_surface^5-2E-9*T_0_pipe_surface^4+4E-
7*T_0_pipe_surface^3-0.0007*T_0_pipe_surface^2+0.5606+440.16;
c_S31803_0=474.51*exp(0.0005*T_0_pipe_surface);
c_S32750_0=476.4*exp(0.0005*T_0_pipe_surface);
    %Argumented vector for specific thermal capacity
    c_pipe_0=[c_K03006_0 c_S31600_0 c_S31803_0 c_S32750_0];

%   Thermal conductivity
k_K03006_0=-4E-16*T_0_pipe_surface^6+1E-12*T_0_pipe_surface^5-2E-9*T_0_pipe_surface^4+1E-
6*T_0_pipe_surface^3-0.0003*T_0_pipe_surface^2-0.0066*T_0_pipe_surface+60.661;
k_S31600_0=0.0143*T_0_pipe_surface+13.964;
k_S31803_0=0.0143*T_0_pipe_surface+13.964;
k_S32750_0=0.0143*T_0_pipe_surface+13.964;
    %Argumented vector for thermal conductivity
    k_pipe_0=[k_K03006_0 k_S31600_0 k_S31803_0 k_S32750_0];

%   Mean cofficient of thermal expansion:
alpha_K03006_0=8E-17*T_0_pipe_surface^6-2E-13*T_0_pipe_surface^5+1E-10*T_0_pipe_surface^4-3E-
8*T_0_pipe_surface^3-4E-6*T_0_pipe_surface^2+0.008*T_0_pipe_surface+11.362;
alpha_S31600_0=-1E-16*T_0_pipe_surface^6+2E-13*T_0_pipe_surface^5-1E-10*T_0_pipe_surface^4+4E-
8*T_0_pipe_surface^3-2E-6*T_0_pipe_surface^2+0.0123*T_0_pipe_surface+15.051;
alpha_S31803_0=-3E-6*T_0_pipe_surface^2+0.0058*T_0_pipe_surface+12.536;
alpha_S32750_0=-3E-6*T_0_pipe_surface^2+0.0058*T_0_pipe_surface+12.536;
    %Argumented vector for mean coefficient of thermal expansion
    alpha_pipe_0=[alpha_K03006_0 alpha_S31600_0 alpha_S31803_0 alpha_S32750_0];

%   Modulus of elasticity:
E_K03006_0=7E-17*T_0_pipe_surface^-6+1E-12*T_0_pipe_surface^5-1E-9*T_0_pipe_surface^4+1E-
7*T_0_pipe_surface^3+6E-6*T_0_pipe_surface^2-0.0646*T_0_pipe_surface+203.66;
E_S31600_0=2E-16*T_0_pipe_surface^6-3E-13*T_0_pipe_surface^5+7E-11*T_0_pipe_surface^4+1E-
8*T_0_pipe_surface^3-1E-5*T_0_pipe_surface^2-0.0656*T_0_pipe_surface+196.14;
E_S31803_0=2E-15*T_0_pipe_surface^6-8E-13*T_0_pipe_surface^5-9E-10*T_0_pipe_surface^4+2E-
7*T_0_pipe_surface^3+4E-5*T_0_pipe_surface^2-0.0655*T_0_pipe_surface+201.82;
E_S32750_0=2E-15*T_0_pipe_surface^6-8E-13*T_0_pipe_surface^5-9E-10*T_0_pipe_surface^4+2E-
7*T_0_pipe_surface^3+4E-5*T_0_pipe_surface^2-0.0655*T_0_pipe_surface+201.82;
    %Argumented vector for modulus of elasticit
    E_pipe_0=[E_K03006_0 E_S31600_0 E_S31803_0 E_S32750_0];

% Determing coefficients at T_1

%   Specific thermal capacity:
c_K03006_1=-2E-14*T_1_pipe_surface^6+4E-11*T_1_pipe_surface^5-2E-8*T_1_pipe_surface^4+7E-
6*T_1_pipe_surface^3-0.0015*T_1_pipe_surface^2+0.549*T_1_pipe_surface+450.79;
c_S31600_1=-2E-15*T_1_pipe_surface^6+4E-12*T_1_pipe_surface^5-2E-9*T_1_pipe_surface^4+4E-
7*T_1_pipe_surface^3-0.0007*T_1_pipe_surface^2+0.5606+440.16;
c_S31803_1=474.51*exp(0.0005*T_1_pipe_surface);
c_S32750_1=476.4*exp(0.0005*T_1_pipe_surface);
    %Argumented vector for specific thermal capacity
    c_pipe_1=[c_K03006_1 c_S31600_1 c_S31803_1 c_S32750_1];

%   Thermal conductivity
k_K03006_1=-4E-16*T_1_pipe_surface^6+1E-12*T_1_pipe_surface^5-2E-9*T_1_pipe_surface^4+1E-
6*T_1_pipe_surface^3-0.0003*T_1_pipe_surface^2-0.0066*T_1_pipe_surface+60.661;
k_S31600_1=0.0143*T_1_pipe_surface+13.964;
k_S31803_1=0.0143*T_1_pipe_surface+13.964;
k_S32750_1=0.0143*T_1_pipe_surface+13.964;
    %Argumented vector for thermal conductivity
    k_pipe_1=[k_K03006_1 k_S31600_1 k_S31803_1 k_S32750_1];

%   Mean cofficient of thermal expansion:
alpha_K03006_1=8E-17*T_1_pipe_surface^6-2E-13*T_1_pipe_surface^5+1E-10*T_1_pipe_surface^4-3E-
8*T_1_pipe_surface^3-4E-6*T_1_pipe_surface^2+0.008*T_1_pipe_surface+11.362;
alpha_S31600_1=-1E-16*T_1_pipe_surface^6+2E-13*T_1_pipe_surface^5-1E-10*T_1_pipe_surface^4+4E-
8*T_1_pipe_surface^3-2E-6*T_1_pipe_surface^2+0.0123*T_1_pipe_surface+15.051;
```

```
alpha_S31803_1=-3E-6*T_1_pipe_surface^2+0.0058*T_1_pipe_surface+12.536;
alpha_S32750_1=-3E-6*T_1_pipe_surface^2+0.0058*T_1_pipe_surface+12.536;
    %Argumented vector for mean cofficient of thermal expansion
    alpha_pipe_1=[alpha_K03006_1 alpha_S31600_1 alpha_S31803_1 alpha_S32750_1];

%   Modulus of elasticity:
E_K03006_1=7E-17*T_1_pipe_surface^-6+1E-12*T_1_pipe_surface^5-1E-9*T_1_pipe_surface^4+1E-
7*T_1_pipe_surface^3+6E-6*T_1_pipe_surface^2-0.0646*T_1_pipe_surface+203.66;
E_S31600_1=2E-16*T_1_pipe_surface^6-3E-13*T_1_pipe_surface^5+7E-11*T_1_pipe_surface^4+1E-
8*T_1_pipe_surface^3-1E-5*T_1_pipe_surface^2-0.0656*T_1_pipe_surface+196.14;
E_S31803_1=2E-15*T_1_pipe_surface^6-8E-13*T_1_pipe_surface^5-9E-10*T_1_pipe_surface^4+2E-
7*T_1_pipe_surface^3+4E-5*T_1_pipe_surface^2-0.0655*T_1_pipe_surface+201.82;
E_S32750_1=2E-15*T_1_pipe_surface^6-8E-13*T_1_pipe_surface^5-9E-10*T_1_pipe_surface^4+2E-
7*T_1_pipe_surface^3+4E-5*T_1_pipe_surface^2-0.0655*T_1_pipe_surface+201.82;
    %Argumented vector for modulus of elastici
    E_pipe_1=[E_K03006_1 E_S31600_1 E_S31803_1 E_S32750_1];

%% Determine the end coefficients on the basis of input.m and this file.
c_0_selection=c_pipe_0(material);
c_1_selection=c_pipe_1(material);
k_0_selection=k_pipe_0(material);
k_1_selection=k_pipe_1(material);
alpha_0_selection=alpha_pipe_0(material)*(10E-6);
alpha_1_selection=alpha_pipe_1(material)*(10E-6);
E_0_selection=E_pipe_0(material)*1000;
E_1_selection=E_pipe_1(material)*1000;
```

Appendix 6 Piping classes (NORSOK.m)

```
% NORSOK piping specifications
%   Piping classes relate to: Wall thickness, inner radius, outer radius
%   and material.

%Sizes - inches:

%   [0.5  0.75  1   1.5   2    3    4     6    8     10    12    14    16    18    20     24 ]
d_o=[21.3 26.7 33.4 48.3 60.3 88.9 114.3 168.3 219.1 273.1 323.8 335.6 406.4 457.0 508.0 610.0];

%   Piping speccs:
% #150  #300    #600    #900   #1500   #2500
%[AC11  BC11    DC11    EC11    FC11    GC11] - Carbon steels
%[AS20  BS20    DS20    ES20    FS20    GS20] - Stainless steel
%[AD20  BD20    DD20    ED20    FD20    GD20] - Duplex
%[AD30  BD30    DD30    ED30    FD30    GD30] - Super duplex

%   Wall thickness matrix:

%       [0.5      0.75    1       1.5     2       3       4       6       8       10      12
14      16      18      20      24]
t_pipe=[4.78     5.56    6.35    5.08    5.54    5.49    6.02    7.11    6.35    6.35    6.35
7.92    7.92    7.92    9.53    9.53;  %AC11
    4.78    5.56    6.35    5.08    5.54    5.49    6.02    7.11    8.18    9.27    10.31   11.13
12.70   14.27   15.09   17.48;  %BC11
    4.78    5.56    6.35    7.14    8.74    7.62    8.56    10.97   12.70   15.09   17.48   19.05
21.44   23.83   26.19   30.96;  %DC11
    4.78    5.56    6.35    7.14    8.74    11.13   11.13   14.27   18.26   21.44   25.40   27.79
30.96   29.36   32.54   38.89;  %EC11
    7.47    7.82    9.09    10.15   11.07   15.24   17.12   21.95   25.00   28.58   33.32   35.71
40.49   45.24   50.01   59.54;  %FC11
    7.47    7.82    9.09    12.50   14.20   17.50   22.20   30.00   36.00   45.00   50.00   55.00
65.00   70.00   80.00   95.00;  %GC11
    2.77    2.87    3.38    3.68    2.77    3.05    3.05    3.40    3.76    4.19    4.57    4.78
4.78    4.78    5.54    6.35;  %AS20
    2.77    2.87    3.38    3.68    2.77    3.05    3.05    7.11    6.35    6.35    8.38    7.92
9.53    9.53    12.70   12.70;  %BS20
    2.77    2.87    3.38    3.68    3.91    5.49    6.02    7.11    10.31   12.70   14.27   15.09
16.66   19.05   20.62   24.61;  %DS20
    3.73    3.91    4.55    5.08    5.54    7.62    8.56    10.97   15.09   18.26   21.44   23.83
26.19   29.36   32.54   38.89;  %ES20
    3.73    3.91    4.55    5.08    8.74    11.13   13.49   18.26   23.01   28.58   33.32   35.71
40.49   45.24   50.01   59.54;  %FS20
    4.78    5.56    6.35    10.15   11.07   15.24   17.50   28.00   36.00   45.00   50.00   NaN
NaN     NaN     NaN     NaN;    %GS20
    2.77    2.87    3.38    3.68    2.77    3.05    3.05    3.40    3.76    4.19    4.57    4.78
4.78    4.78    5.54    6.35;  %AD20
    2.77    2.87    3.38    3.68    2.77    3.05    3.05    3.40    3.76    6.35    6.35    6.35
6.35    7.92    9.53    9.53;  %BD20
    2.77    2.87    3.38    3.68    3.91    5.49    6.02    7.11    8.18    9.27    9.53    11.13
12.70   12.70   12.70   17.48;  %DD20
    2.77    2.87    3.38    3.68    3.91    5.49    6.02    7.11    10.31   12.70   14.27   15.09
16.66   19.05   20.62   24.61;  %ED20
    2.77    2.87    3.38    3.68    5.54    7.62    8.56    14.27   18.26   21.44   25.40   27.79
26.19   29.36   32.54   38.89;  %FD20
    3.73    3.91    4.55    7.14    8.74    11.13   13.49   21.95   25.00   32.00   36.00   40.00
40.49   45.24   50.01   59.54;  %GD20
    2.77    2.87    3.38    3.68    2.77    3.05    3.05    3.40    3.76    4.19    4.57    4.78
4.78    4.78    5.54    6.35;  %AD30
    2.77    2.87    3.38    3.68    2.77    3.05    3.05    3.40    3.76    4.19    4.57    4.78
6.35    6.35    9.53    9.53;  %BD30
    2.77    2.87    3.38    3.68    2.77    3.05    3.05    7.11    6.35    7.80    8.38    9.53
9.53    9.53    12.70   14.27;  %DD30
    2.77    2.87    3.38    3.68    3.91    5.49    6.02    7.11    10.31   12.70   14.27   15.09
12.70   14.27   20.62   24.61;  %ED30
    2.77    2.87    3.38    3.68    3.91    5.49    8.56    10.97   15.09   18.26   21.44   23.83
21.44   23.83   26.19   30.96;  %FD30
    3.73    3.91    4.55    5.08    8.74    11.13   13.49   18.26   23.01   28.58   33.32   35.71
36.53   39.67   44.45   52.37]; %GD30
```

```
%   Switch table(1 if thick walled, 0 if thin walled - based on r/t ratio of 10):

hoop_stress=[1  1   1   1   1   1   1   0   0   0   0   0   0   0   0   0;
    1   1   1   1   1   1   1   0   0   0   0   0   0   0   0   0;
    1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1;
    1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1;
    1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1;
    1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1;
    1   1   1   1   1   0   0   0   0   0   0   0   0   0   0   0;
    1   1   1   1   1   0   0   0   0   0   0   0   0   0   0   0;
    1   1   1   1   1   1   1   0   1   1   0   0   0   0   0   0;
    1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1;
    1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1;
    1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1;
    1   1   1   1   1   0   0   0   0   0   0   0   0   0   0   0;
    1   1   1   1   1   0   0   0   0   0   0   0   0   0   0   0;
    1   1   1   1   1   1   1   0   0   0   0   0   0   0   0   0;
    1   1   1   1   1   1   1   0   1   1   0   0   0   0   0   0;
    1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1;
    1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1;
    1   1   1   1   1   0   0   0   0   0   0   0   0   0   0   0;
    1   1   1   1   1   0   0   0   0   0   0   0   0   0   0   0;
    1   1   1   1   1   0   0   0   0   0   0   0   0   0   0   0;
    1   1   1   1   1   1   1   0   1   1   0   0   0   0   0   0;
    1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1;
    1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1];

%   Pipe radius

 r_o=d_o/2;                 %outside radius - vector
 r_o_pipe=[r_o; r_o; r_o; r_o; r_o; r_o ;r_o; r_o;
     r_o; r_o; r_o; r_o; r_o; r_o; r_o; r_o;
     r_o; r_o; r_o; r_o; r_o; r_o; r_o; r_o];
 r_i_pipe=r_o_pipe-t_pipe;  %inside radius

 r_i_pipe_selection=r_i_pipe(piping_spec,nominel_diameter);
 r_o_pipe_selection=r_o_pipe(piping_spec,nominel_diameter);
 t_pipe_selection=t_pipe(piping_spec,nominel_diameter);
 hoop_stress_selection=hoop_stress(piping_spec,nominel_diameter);
```