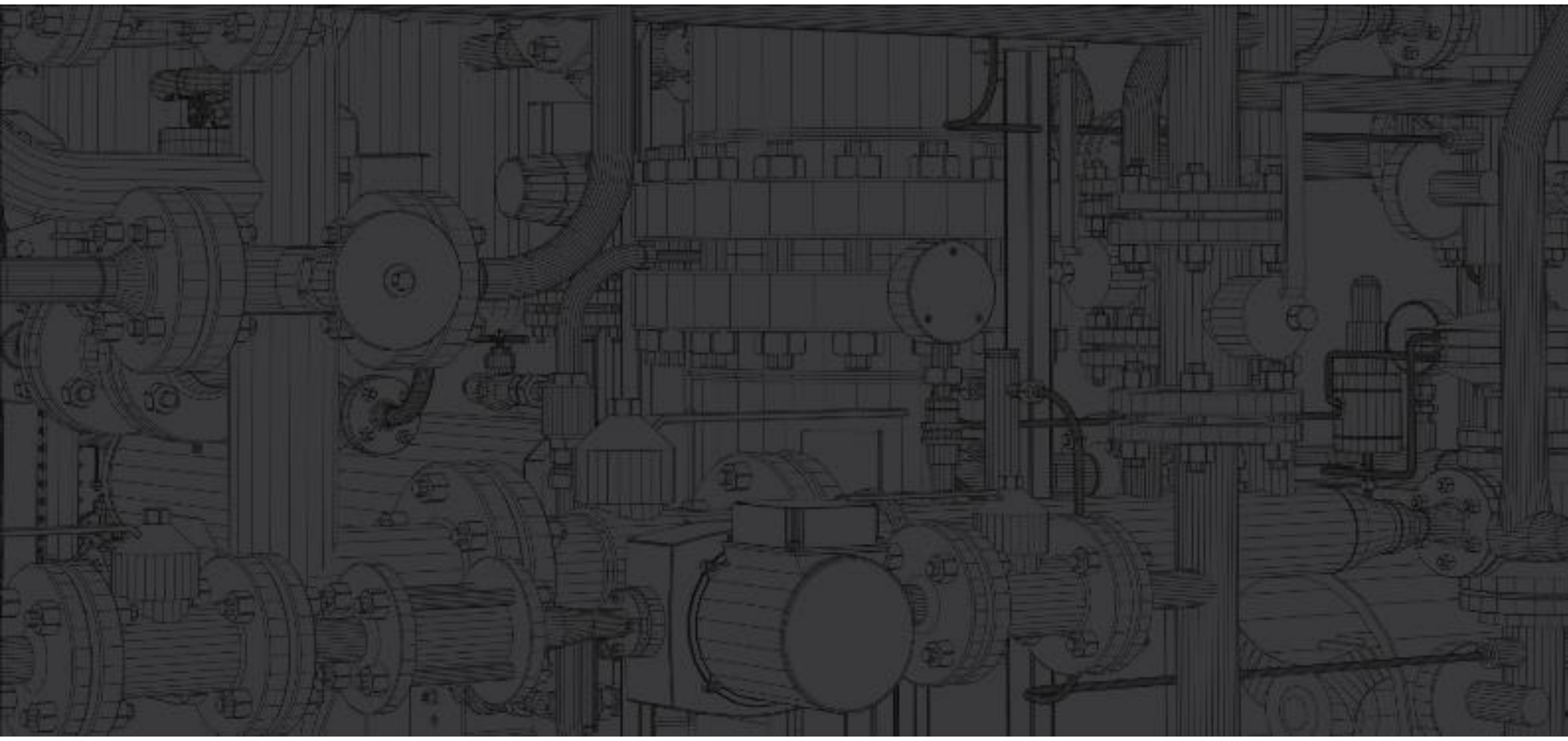
TECHNICAL MEMO

“INDUCTION BENDS STRESSMAN ENGINEERING’s AS-PER-TODAY KNOWLEDGE”

100103–TM–001–REV 2



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Rev 2	IFI	21.02.2017	SLH	BDJ	HSH
Rev 1	IFI	08.12.2016	SLH	BDJ	HSH

Summary:
This technical memo describes Stressman Engineering's (Stressman) current knowledge, information and theories regarding induction bends from a mechanical engineering perspective.

Stressman has worked closely together with NIRAS to research their induction bends. NIRAS is world leading in induction bending of pipes and beam profiles.

ASME B31.3 Section II is used as baseline and reference for the work performed in the research. Other standards and guidelines will be evaluated in the future.

Disclaimer:
The knowledge in this document should be considered as a **guideline** and may not cover all aspects, combinations and situations, and Stressman does **not** take any responsibility of how the knowledge is utilized. It is the reader's responsibility to evaluate the knowledge and information given herein.

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1 INTRODUCTION

1.1 Purpose, Scope and Limitations

The purpose of this technical memo is to summarize Stressman Engineering's knowledge regarding induction bends. All physical studies are based on NIRAS' bends. Other manufacturers may not comply with NIRAS' quality and methods and therefore caution must be used when other manufacturers are being used.

This study is linked to NIRAS' bending process. NIRAS' is world leading with regards to controlling the induction bending process which ensures that for example the material quality is as desired, transitions zone are smooth and more. The study is therefore limited to NIRAS' induction bends.

1.2 What's induction bending?

Induction bending is a method that allows the bending of any material that conducts electricity. This technology applies a bending force to a material that has been locally heated-up by an eddy current induced by a fluctuating electromagnetic field.

To ensure uniform heating without the risk of overheating, the temperature is computer controlled and regulated via an infrared camera.

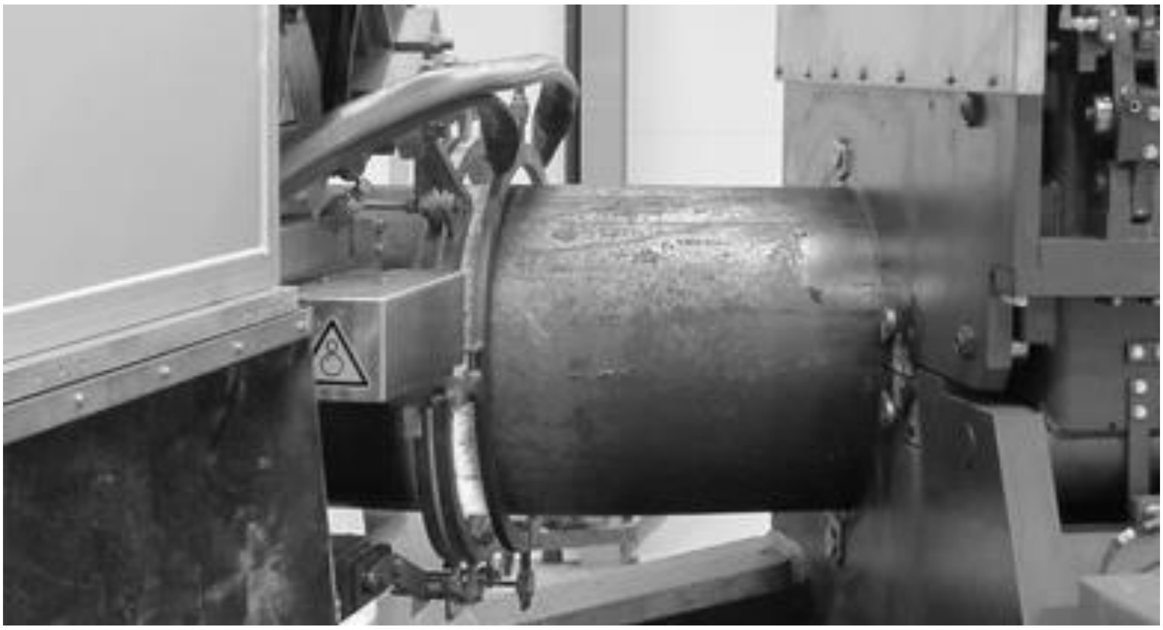


Figure 1: Induction bend machine

More details can be found at http://www.niras.no/ and by contacting NIRAS.

1.3 Why use induction bending?

To summarize the benefits:

- Less welding
- Much shorter production time
- Variable bend radius, for example a longer radius will give a smaller pressure drop and reducing the response due to slugging
- Custom bend angle (not limited to 90, 45, 30 degree bends)
- Summarized; leaner, meaner and cleaner designs

Figure 2: Induction bent pipe spools

1.4 Why is it not more used?

There is some resistance against using induction bends in the industries. The main sources of this resistance are;

1. Fairly new process
2. Wall thinning of extrados
3. Possible alternation of the material properties

1.4.1 Fairly new process

The induction bending process is fairly new process compared with using standard bends and welding. Going from something that has a field record of more than 100 years is difficult to change. The induction bending process has been used successfully over the past 30 years, which means that the process is also having a substantial track record.

1.4.2 Wall thinning extrados

The effects of wall thinning of the extrados will be addressed in this technical memo. Ordinary standard ASME B16.9 bends does also have wall thickness thinning on the extrados and thickening on the intrados in the same matter as the induction bends.

1.4.3 Alternation of material properties

With sufficient process control, material properties of a series of corrosion resistant alloys (CRA) can be maintain after bending with no further heat treatment due to the integrated quenching operation. For high wall thickness CRA and for carbon steels the bending operation must be followed by a full body heat treatment to restore material properties. Each dimension and grade is qualified to ensure that material properties in the bended area meets the requirement of the mother pipe.

2 INDUCTION BENDING – WHAT HAPPENS TO THE GEOMETRY?

This chapter summarizes what is happening to the geometry during the induction bending.

2.1 Thinning and thickening

The intrados and extrados change due to the compression and tension. The pipe is heated to very high temperatures and this ensures that only very small residual stresses get trapped in the bend.

During the induction bending process the pipe wall thickness will be thickened in the intrados and thinned in the extrados. The wall thickness at the centerline will be unchanged.

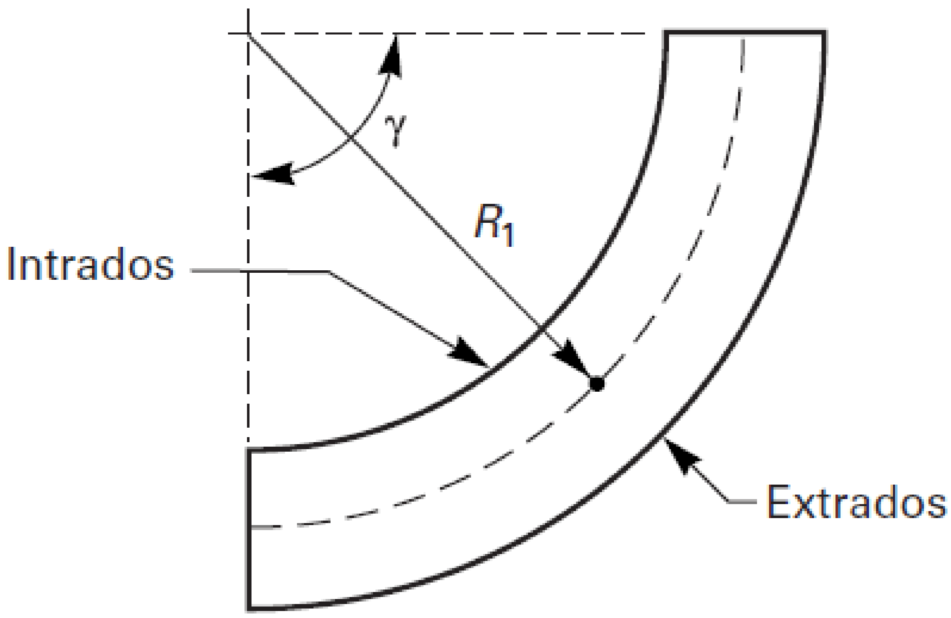


Figure 3: Nomeclature

2.2 Shape after bending

Since no material is disappearing and there is no tension or compression, the cross-sectional area is the same as before. Hence, it is easy to calculate the thinning of the extrados and thickening of the intrados based on the geometrical ratios.

	Extrados	Intrados
Radius at intra- and extrados	$R_{extrados} = R_1 + \frac{OD}{2} - \frac{T}{2}$	$R_{intrados} = R_1 - \frac{OD}{2} + \frac{T}{2}$
Wall thinning/thickening in %	$(1 - R_1/R_{extrados})/100$	$(R_1/R_{intrados} - 1)/100$
New thickness	$T_{ext} = T * R_1/R_{extrados}$	$T_{int} = T * R_1/R_{intrados}$

where R_1 = bend radius, OD = Outer diameter of pipe and T = wall thickness

These formulas has been physically verified in most of NIRAS' projects, as well as our experimental study. A thing to notice is the smooth transition zones in the start and end of the induction bends, see Figure 4.

Figure 4: Cross section of NIRAS' induction bends

The Figure 4 shows the in-plane cross section after bending of a 6" Sch 120 2D bend. This pipe has the following parameters, OD = 168.3mm, T = 14.3mm and R1 = 2*168.3mm = 336.6mm. The T value used in the example below are based on the average of the real values measured.

	Extrados	Intrados
Radius at intra- and extrados	$R_{extrados} = 336.6 + \frac{168.3}{2} - \frac{(14.54 + 14.83)}{2 * 2}$ $R_{extrados} = 413.4mm$	$R_{intrados} = 336.6 - \frac{168.3}{2} + \frac{(14.44 + 14.35)}{2 * 2}$ $R_{intrados} = 259.6mm$
Wall thinning/ thickening in %	Thinning % = 1 – 336.6/413.4 Thinning % = 18.6%	Thickening % = 336.6/259.6 – 1 Thickening % = 29.7%
New thickness	$T_{ext} = \frac{(14.54 + 14.83)}{2} * \frac{336.6}{413.4} = 12.0mm$	$T_{int} = \frac{(14.44 + 14.35)}{2} * \frac{336.6}{259.6} = 18.7mm$
Real thickness	11.9mm	$\frac{(19.12 + 18.76)}{2} = 18.9mm$
Variance	0.1mm	0.2mm

The variance is due to changes of the mill tolerance and inaccuracy when measuring the wall thickness.

2.3 Sectional modulus

The sectional modulus is not that much changed much since the cross-sectional area is the same as before. This change is also accounted for in the SIFs. It is only the ID and OD that shifts slightly out of center. The same effect is also happening for standard B16.9 bends. This small shift is included in safety factor of the pipe stress codes.

3.1 Pressure containment

A piping component should never be weaker than the run pipe. Therefore, it is important to verify that the pressure containment is within the limits given by codes and regulations, such as ASME B31.3. Stressman has also performed several stress calculations for verifying the code formulas.

3.1.1 ASME B31.3 Calculations of Pipe Bends

ASME B31.3 address pipe bends in chapter II section 304.2.1. The method is based on a modified wall thickness formula. The I in the formula below is depended on intrados or extrados.

$$t = \frac{PD}{2[(SEW/I) + PY]}$$

$\boldsymbol{P}$ = internal pressure	$\boldsymbol{D}$ = outside diameter of pipe
$\boldsymbol{S}$ = allowable stress from table A1	E = quality factor from table A1-A or A-1B
$\boldsymbol{W}$ = Weld joint strength factor from 302.3.5(e)	Y = Coefficient from table 304.1.1

The I is a factor that is depended on the intrados and extrados.

Intrados	Extrados
$I = \frac{4(R_1/D) - 1}{4(R_1/D) - 2}$	$I = \frac{4(R_1/D) + 1}{4(R_1/D) + 2}$

The I factor will always be above 1 for the intrados and below 1 for the extrados. In other words the B31.3 code states that the intrados needs to be thicker than the straight pipe and vice versa.

3.1.2 Stressman's Pipe Bend Calculation Method

Stressman has a method that proves the formulas in the B31.3 method. This method is based on comparing areas together. Please see appendix A for the formula and example.

3.1.3 FEA – No change in wall thickness, linear material model

An FEA with no change in the wall thickness was made to also confirm the methods above. The purpose of the FEA was to evaluate the stress increase and decrease in the intrados and extrados. The Hoop stress is 1MPa in the model, while the max and min stress intensity is 1.48 and 0.83.

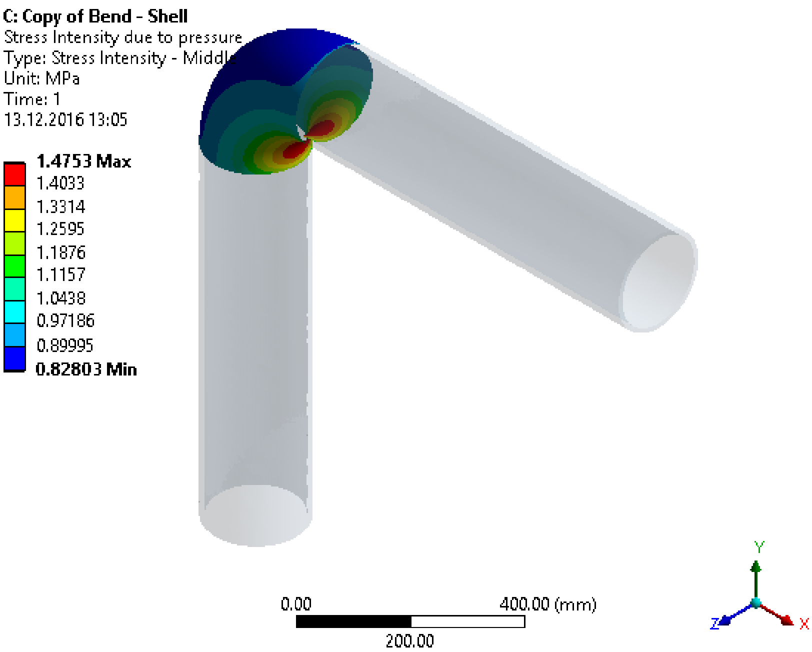


Figure 5: FEA of pressure

3.1.4 Summary pressure containment

The table below shows the correspondence between ASME B31.3, Stressman's method and FEA. Input used: bend radius R = 200mm, outer diameter D = 200mm and wall thickness T = 10mm.

Table 1: Summary of pressure containment

Bend location	ASME B31.3	Stressman's method	FEA
Intrados	1.50	1.48	1.48
Extrados	0.83	0.83	0.83

As the table above shows, the three methods correspond well with each other. Therefore, the conclusion is that the ASME B31.3 method can be used for induction bends.

3.2 Physical study and experiment– FEA vs pipe bursting

A study has been conducted together with NIRAS to evaluate the real burst pressure. The study was also partially funded by the Norwegian Research Council. The induction bend geometry was based on the real measured dimensions after bending. A 6" pipe with a nominal wall thickness of 14.3mm was used in the experiment.

Figure 6: Arranging the experiment

3.2.1 Material model

The input to the material model was based on the average of what the material tests showed. The material model used in the analysis was built per ASME VIII Division 2.

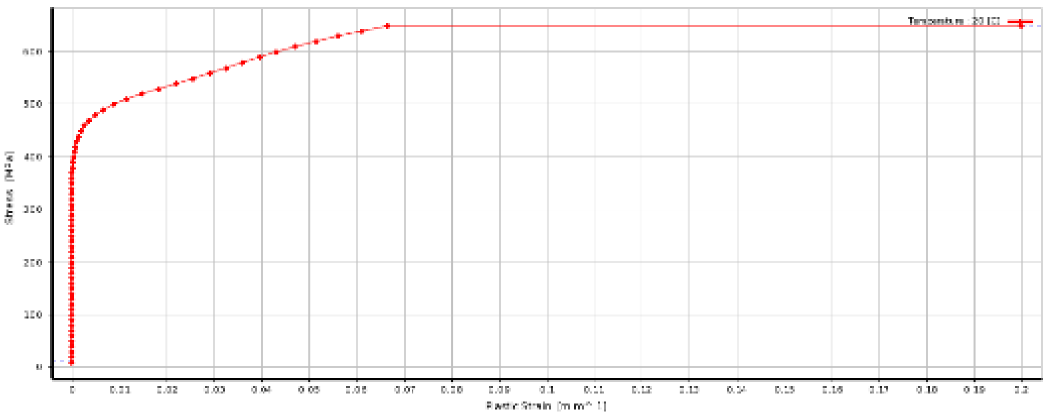


Figure 7: Material model of duplex (based on test data and ASME VIII division 2)

3.2.2 Results and benchmarking

The FEA showed that large plastification of the pipe would happen just above 1300bar, which indicates the burst pressure. The analysis also found a solution for 1400bar, but that might be due to too large time stepping in ANSYS. The pipe bursted at 1300bar, which is in good correspondence with the analysis. In 2017 more comprehensive analyses will be performed.

Figure 8: Close up of the crack

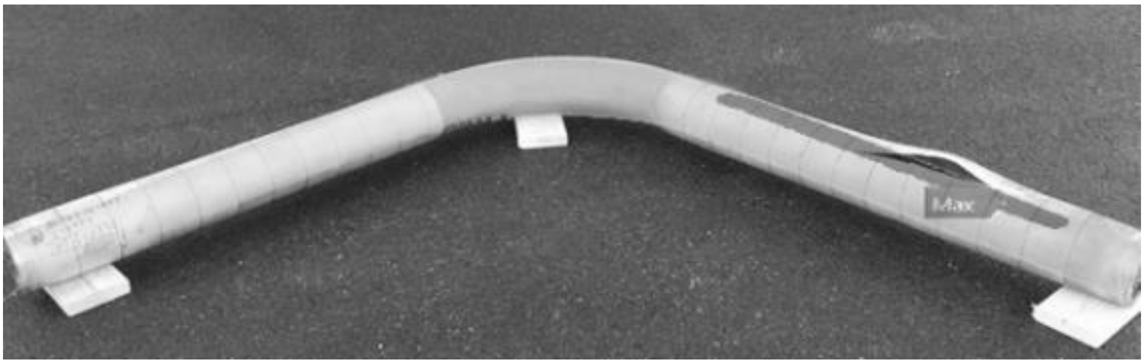


Figure 9: Bursted pipe with FEA results

As it can be seen from the figure above, the pipe bursted in the predicted area.

3.2.3 Error sources

The following error sources are identified:

- Averaged material properties
- Mill tolerance
- Mesh
- Too large timestepping

3.2.4 Continuation of the study and experiments

The study will be continued next year to cover the error sources, more dimensions, materials and bend radiuses. This document will be updated accordingly.

3.3 Physical burst testing (in addition to our study)

NIRAS and their clients have performed several burst tests of pipes with various sizes and each of the tests bursted in the tangent pipe away from the bends. The pictures below show some examples:

Figure 10: Bursted pipes

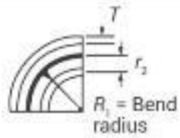
3.4 Combined loadings

A bend is often exposed to other loads such as bending moments in addition to the internal pressure. These loads are determined with a flexibility analysis. The flexibility analysis is based on beam element theory, which cannot predict the exact behavior of piping bends due to simplifications. Therefore are stress intensification factors and stiffness factors used in the analyses.

3.4.1 ASME B31.3 Appendix D – SIF and flexibility factor

Since the beam element theory cannot predict the exact capacity of piping components the piping codes introduces SIFs for piping components. For piping, the formula has been unchanged since the 1950s, when introduced by Markl. The SIFs for bends are described as:

Table D300[1] Flexibility Factor, K, and Stress Intensification Factor, i

Description	Flexibility Factor, K	Stress Intensification Factor [Notes (2) (3)] Out-of-Plane i_o	In-Plane i_i	Flexibility Characteristic, h	Sketch
Weilding elbow or pipe Bend [Notes (2) (4)-(7)]	$\frac{1.65}{h}$	$\frac{0.75}{h^{2/3}}$	$\frac{0.9}{h^{2/3}}$	$\frac{TR_1}{r_2^2}$	

Where, T = Nominal wall thickness, R_1 = bend radius, r_2 = average radius of pipe (D+d)/4, where D = outer diameter, d = inner diameter

As it can be clearly seen the SIF is highly dependent on the bend radius, which is logical since a smoother transition decreases any stress concentrations.

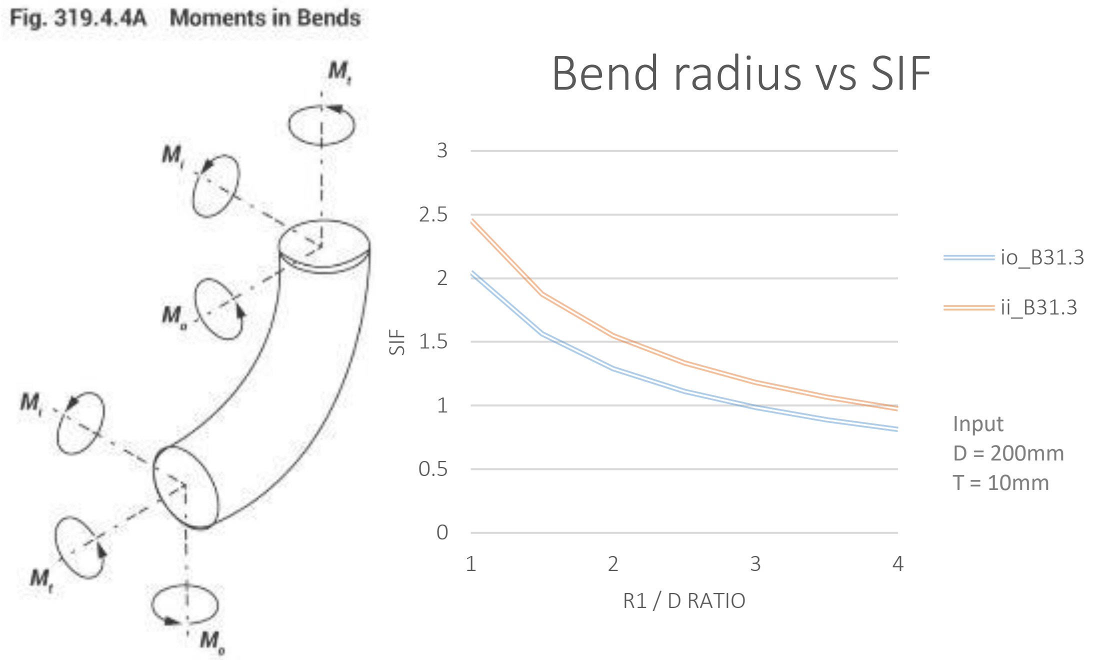


Figure 11: In- and out-of-plane directions for bends and graph showing bend radius vs. SIF

3.4.2 FEA SIF calculations

Two parametric FEA studies has been performed and compared with ASME B31.3 SIFs. The first study was set up with an shell element model, no change of wall thickness was accounted for. Meaning that the nominal pipe wall thickness was used. The second study was based on solid elements and incorporated the thinning and thickening of the bend. Both studies shows that the calculated SIFs either tangent the B31.3 SIFs or are below.

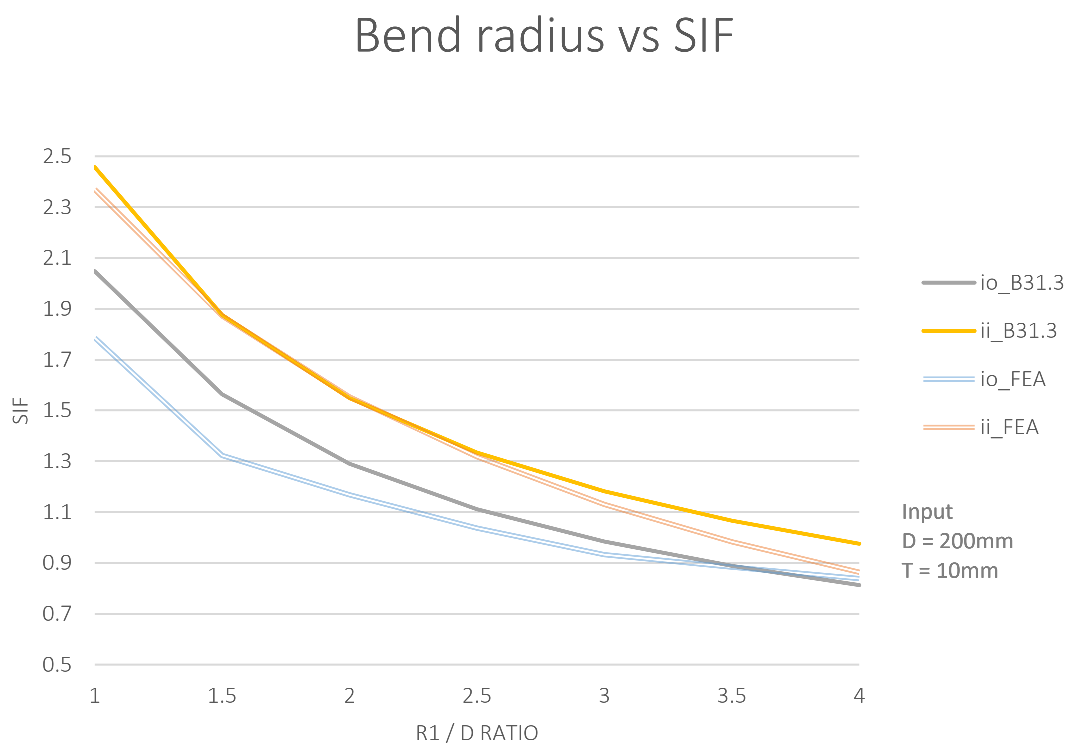


Figure 12: Shell analysis – Bend radius vs. SIF

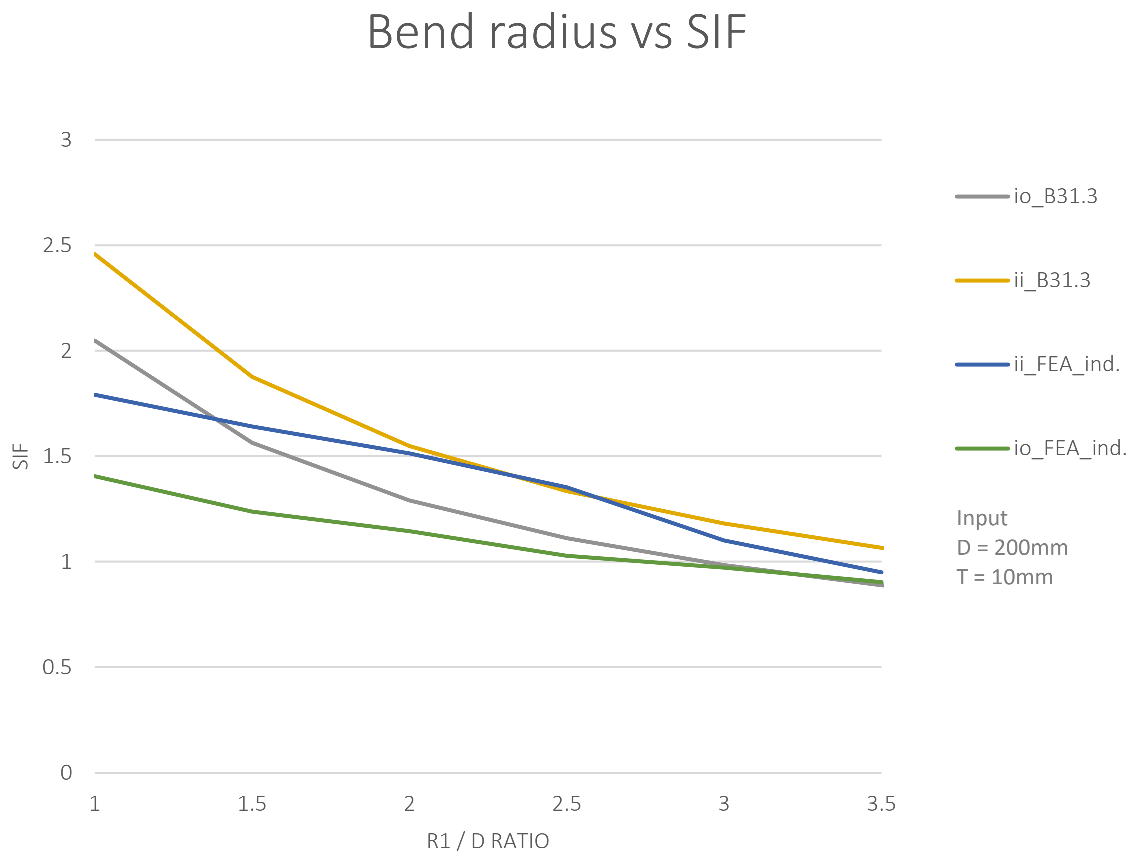


Figure 13: Solid element analysis – Bend radius vs. SIF

3.5 Pressure drop over bend

Using a larger bending radius is beneficial for the pressure drops in the piping. The graph shows the bend radius ratio (R/D) against the equivalent length. As it clearly shows increasing the bend ratio to 2.5 is clearly beneficial and can decrease the operational costs of the system.

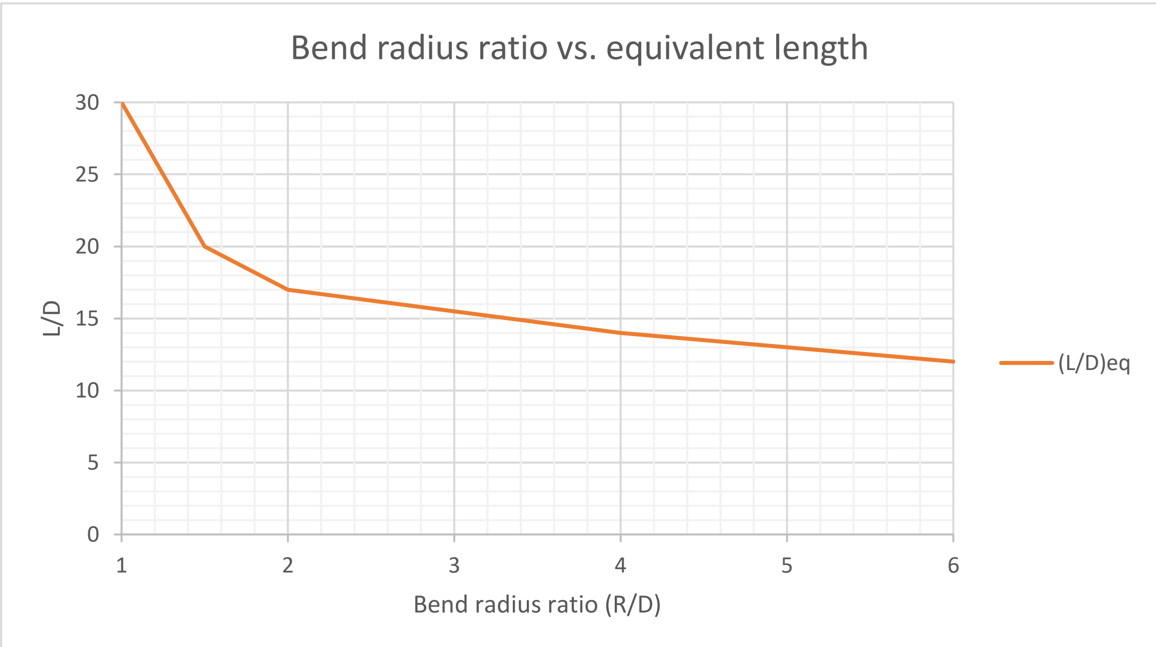


Figure 14: Pressure drop over bends

4 SUMMARY – How to apply the knowledge?

There are two main topics that should be checked. Firstly, the pressure containment of the bend must be checked. Secondly, if the pipe is a critical pipe, then a flexibility analysis should be performed and evaluated.

FEA may in some occasions be necessary, but typically not for topside piping.

4.1 Verify the pressure capacity – Hand calculation

Use the formulas given in ASME B31.3 Chapter II paragraph 304 "Pressure design of components" regarding wall thickness (304.1.2) and bend calculations (304.2.1). The main formulas are also stated in chapter 3.1.1 of this report.

4.2 Pipe Stress Analysis – Flexibility

The hand calculations referred to in chapter 4.1 should **always** be performed. If the pipe is defined as a critical pipe, then a pipe stress analysis (also called flexibility analysis) should be performed of the piping system. For duplex and super duplex piping used subsea a FEA may also be required due to Hydrogen Induced Stress Cracking (HISC).

4.2.1 Pipe stress modelling

The induction bends can be included as standard bends in the pipe stress software. As stated in chapter 2.2 the sectional modulus is not changed and therefore it is not necessary to include change of wall thickness in the pipe stress analysis, as long as a hand calculation is performed. SIFs and flexibility factors from the relevant piping code can be used in the setup.

4.2.2 FEA modelling

The 3D model geometry setup described in chapter 2.2 can be used. Then apply the relevant material, boundary conditions and loads. Check the stresses and/or strain against the relevant code such as ASME VIII D2/D3, DNV-RP-F112. Stressman do normally extract loads or displacements from a global beam element analysis and applies these loads to the local components such as bends.

NOTE:
To stay tuned for updated regarding induction bends and other studies that we perform, please drop us an e-mail at post@stressman.no to stay tuned.

5 STRESSMAN ENGINEERING – WHO ARE WE and WHAT DO WE DO?

First of all, thank you for reading our document regarding induction bends. If you have any comments, please submit them to post@stressman.no.

Our mission at Team Stressman is to become the preferred supplier of quality computational analyses. Our passion for the job is what drives us. At Stressman, all projects are completed in-house and we benefit from owning all the necessary software, licenses and insurances as standard, in order to function independently.

We believe strongly in our slogan: "**Relax, let us handle your stress**". We take pride in our methods of providing clients with assurance and credible, reliable solutions. Over time we have recognized our potential to grow our business outside of our native Norway. And in order to compete with the lower cost Asian countries, we have collated all our knowledge and systemized it through the use of macro systems and internal work processes.

5.1 Engineering Services

Whenever we take on a new project, we always emphasize that the most synergies will be when we have conducted as many of the mechanical analyses as possible. When we get to calculating for example piping, pipe support and structure of a skid, it is very easy for us to optimize the overall performance, as we have full control of the boundaries and loads.

Having a detailed understanding of the How of Why of industry standards, both historically and currently, has meant we utilize them more effectively and even challenge them on occasion. This is also very important when in discussion with third party organizations.

We like to say that because we know the physics, we can come up with the solution. The list below provides a breakdown of our competence and ability in the most common mechanical engineering analysis fields:
- General static and dynamic physical problems
- Pipe stress analysis (Caesar II and Triflex)
- Pressure vessel and tank calculations (PVElite and NozzlePro)
- Structural calculations (SAP2000 and ANSYS)
- Conceptual Design and R&D, early phase evaluations and optimizations
- Finite Element Analysis (ANSYS Enterprise)
- Fracture Mechanics
- Computational Fluid Dynamics (CFD)
- Marine operations and Risers (Orcaflex)
- Explicit dynamics

Stressman Engineering has been certified in accordance with ISO9001 since 2012. Our quality management system is incorporated in all of our processes to ensure the continued good quality of our services.

5.2 Engineering Courses – The Stressman Engineering Academy

The Academy's mission is to provide the participants with the best, latest and most interesting vocational engineering courses and to refuel you with inspiration and knowledge. A high focus on why instead of how will give you a better understanding, possibilities for optimization and cost reduction, as well as a base for deeper discussions with colleagues, vendors and clients. Our knowledge originates from the North Sea outside of Norway.

We are covering topics within the field of mechanical stress calculations and computational fluid dynamics. Our pipe stress course has been quite successful with wonderful feedback. We can also compose in-house training to your specifically needs.

You should expect nothing but the best. Every aspect of the course should be of the outmost premium quality. It is not only our goal to give you a better understanding of the better topics, but also to give you an experience for life and connect with other fellow peers. When attending the course, the participants get a USB-stick filled with calculators and solved examples. SEA conducts internal research which is shared with the participants in our events.

Please visit www.stressmanacademy.com for more details.

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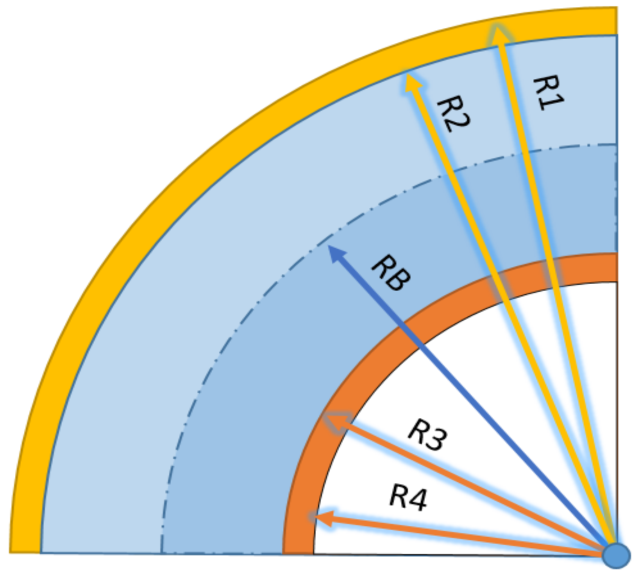
Stressman's method for validation of B31.3 I-factors



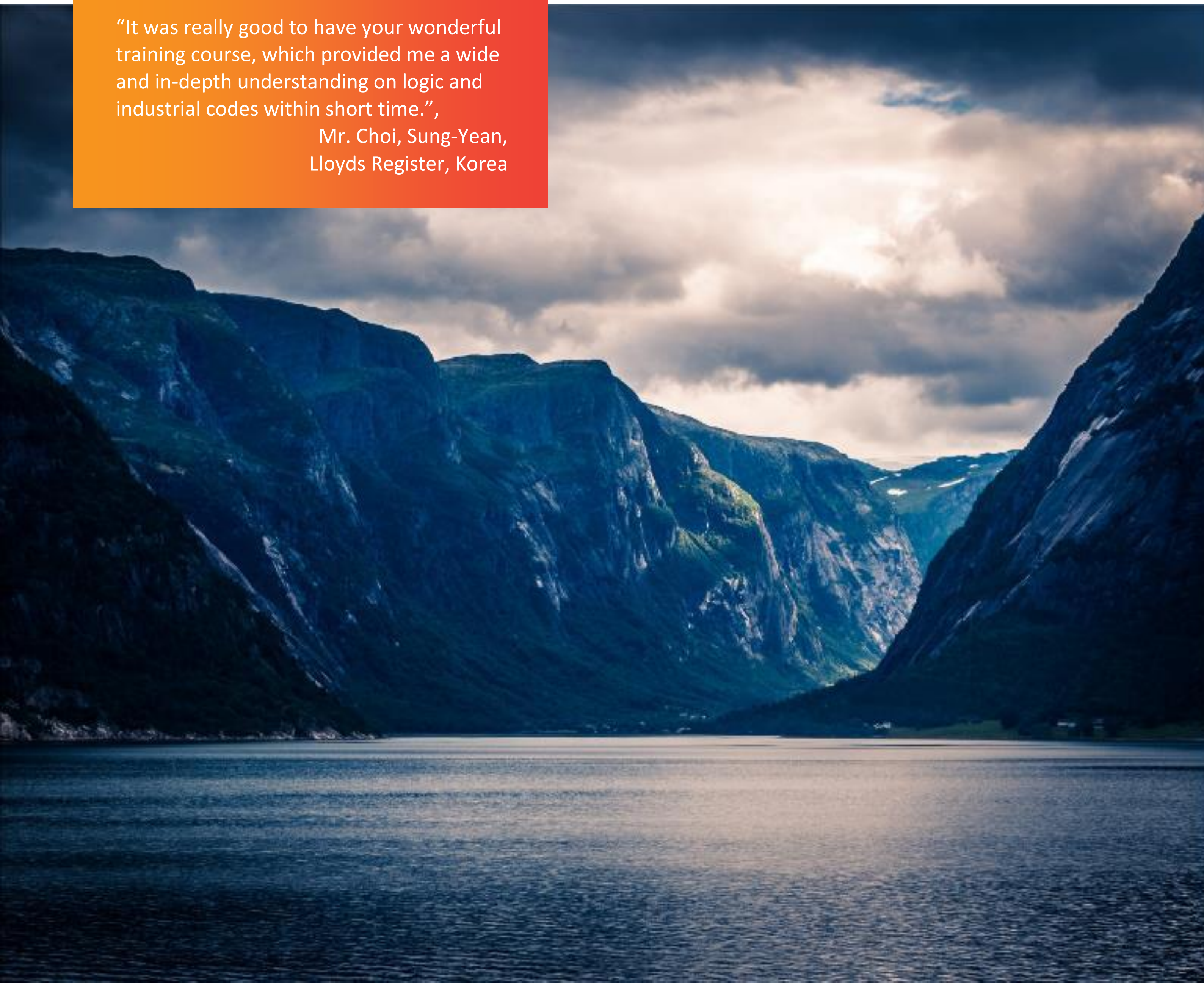
Input	Description	Value	Units	Formula
OD	Outer diameter	200	mm	Input
WT	Wall thickness	10	mm	Input
RB	Bend radius	200	mm	Input
P	Pressure	0.1	MPa	Input
Output				
$S_{HoopPipe}$	Hoop stress in straight pipe	0.9	MPa	
R1	Radius extrados outside	300.0	mm	RB+OD/2
R2	Radius extrados inside	290.0	mm	RB+OD/2-WT
R3	Radius intrados inside	110.0	mm	RB-OD/2+WT
R4	Radius intrados outside	100.0	mm	RB-OD/2
A_{ext_WT}	Area extrados	4634	mm^2	$\pi(R1^2-R2^2)/4$
A_{ext_P}	Area pressure extrados	34636	mm^2	$\pi(R2^2-RB^2)/4$
A_{int_WT}	Area intrados	1649	mm^2	$\pi(RB^2-R3^2)/4$
A_{int_P}	Area pressure intrados	21913	mm^2	$\pi(R3^2-R4^2)/4$
F_{ext}	Force due to pressure on extrados	3464	N	$A_{ext\_P}*P$
F_{int}	Force due to pressure on intrados	2191	N	$A_{int\_P}*P$
S_{ext}	Stress extrados	0.75	MPa	F_{ext}/A_{ext_WT}
S_{int}	Stress intrados	1.33	MPa	F_{int}/A_{int_WT}
F1	Stress intensifaction factor extrados	**0.83**	-	$S_{ext}/S_{HoopPipe}$
F2	Stress intensifaction factor intrados	**1.48**	-	$S_{int}/S_{HoopPipe}$
F1	ASME I factor extrados	**0.83**	-	((4*(RB/OD))+1)/((4*(RB/OD))+2)
F2	ASME I factor intrados	**1.50**	-	((4*(RB/OD))-1)/((4*(RB/OD))-2)

"I really enjoyed your workshop a lot and you are one of my biggest inspirations as a stress analysis engineer",

Mr. Hossain, Mohammad Tanvir,
Sembcorp Marine TK Yard, Singapore

"It was really good to have your wonderful training course, which provided me a wide and in-depth understanding on logic and industrial codes within short time.",

Mr. Choi, Sung-Yean,
Lloyds Register, Korea



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