

TECHNICAL REPORT

JOINT INDUSTRY PROJECT

RELIABILITY OF CORRODED PIPES
FINITE ELEMENT ANALYSES

REPORT No. 96-3392

REVISION No. 01

DET NORSKE VERITAS



TECHNICAL REPORT

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CONCLUSIVE SUMMARY

1 CONCLUSIVE SUMMARY

This report is one in a series of 4 reports in the JIP project "Reliability of Corroded Pipes". The objective of the project has been to provide burst capacity and acceptance formulas with consistent reliability levels for corroded pipes.

The work includes a series of laboratory tests and a large number of FE analyses of corroded pipes exposed to internal pressure and combined internal pressure and external compressive loading. Both longitudinal and circumferential corrosion are considered.

This report describes the finite element analyses of pipes with simulated smooth corrosion defects.

A large number of finite element analyses were performed to estimate the burst capacity of corroded pipes covering variations in parameters as the pipe diameter, the wall thickness, length and depth of the corrosion defect, shape of the corrosion defect, combined loading and material properties. Both longitudinal corrosion and circumferential corrosion defects were included in the study.

In this report the analyses are described, which includes description of the models, the parameters studied, the solution strategies, etc. and the main conclusions. The failure criterion for the analyses with applied internal pressure was adopted from the work by British Gas (Fu and Kirkwood), and a strain criterion was applied for the analyses with combined loads.

The analyses, in combination with the laboratory tests performed within the project, forms the background for the development of the capacity equation and the calibrated design equation for corroded pipes, which is described in the project report "Reliability of Corroded Pipes, Assessment of Capacity and Acceptance Criteria."



INTRODUCTION

2 INTRODUCTION

2.1 Motivation

A pipeline is a large financial asset for the pipeline operator and a safe operation of the pipeline is therefore of great concern. On the other hand, unnecessary repair and an over conservative operation of the pipeline may result in high costs and unexploded resource utilisation. As the pipelines are ageing and corrosion may develop, the economical consequences of reduced operation pressure, repairs, or replacements may become high.

Existing design codes for burst strength assessment of corroded pipes have a inconsistent safety level for varying degree of corrosion, which may result in both hazardous designs or possibly costly and unrequired requalification actions. Available acceptance equations for assessment of allowable operating pressures of degraded pipelines depending on the selected reliability level are therefore desirable.

When severe corrosion has been observed in a pipeline, the selection of required action to be carried out should be based on an overall assessment of the pipeline, where uncertainties associated with both the assessment of the degree of corrosion and the capacity evaluation should be considered. Repair or replacement of the pipeline should be avoided, or postponed in time, if this is possible within the safety requirements defined. Required actions should further also be initiated in order to maintain the integrity of the pipeline and to avoid an undesired risk exposure of the pipeline.

2.2 Background

The present Joint Industry Project "Reliability of Corroded Pipes" is a continuation of the project "Residual Strength of Corroded and Dented Pipes". The former project, Phase I, was started in 1993 and concluded at the end of 1995. The present project, Phase II, stared shortly after.

The Phase I of the project was sponsored by Statoil, Phillips, Brasoil (Petrobras), Mineral Management Services (MMS), Norwegian Petroleum Directorate (NPD), The Research Council of Norway (NFR), and Det Norske Veritas (DNV).

The Phase II of the project "Reliability of Corroded Pipes" is sponsored by Statoil, Amoco, Exxon, NPD, MMS and Brasoil (Petrobras).

The project scope of work has been modified during the course of the project to better utilise the funding. Especially, the work conducted by British Gas in a corresponding project has had an impact on the course of this project.

To avoid unnecessary overlapping, the initial scope was changed to covering the development of capacity and acceptance equations for combined internal pressure and external loading for both longitudinal corrosion and circumferential corrosion, where the acceptance equation for longitudinal corrosion was based on a probabilistic calibration. The basis for such a development was a series of finite element analysis and a reduced series of laboratory test compared to the initial scope.



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British Gas had prior to the initiation of Phase II of the project performed several laboratory tests and finite element analyses for internal pressure only, accounting also for the interaction of separate pits and grooves. However, this work would not include a probabilistic calibration of an acceptance (design) equation. A merging of the outcome from the DNV and the British Gas projects would therefore be natural.

The advantage with a co-operation between the DNV and the British Gas projects would be that the obtained capacity and acceptance equations in the DNV project could be calibrated to a larger database. A set of common recommended capacity and acceptance design equations from the DNV and British Gas projects could then be proposed, which would also likely receive a higher recognition in the marked.

Such a co-operation could be initiated after the completion of both the DNV and the British Gas projects, by the development of a unified guideline for burst of corroded pipes.

2.3 Project Reports

The project concludes with the reports defined in Table 2-1.

Table 2-1 Overview of the project reports

DNV report no.	Title / Subject
96-3392	Reliability of Corroded Pipes / Finite Element Analyses
96-3393	Reliability of Corroded Pipes / Laboratory Burst Tests
96-3394	Reliability of Corroded Pipes / Assessment CG
97-3358	Reliability of Corroded Pipes / Assessment of Capacity and Acceptance Criteria Reliability of Corroded Pipes / Project Guideline

2.4 Participants and their Representatives

The following organisations participated in the project;

Participant Minerals Management Service (MMS)	Representative	Telephone /	Fax
Norwegian Petroleum Directorate (NPD)	Wallace O. Adcox	Telephone Fax	(+1) 703 787 1354 (+1) 703 787 1010
Den norske stats oljeselskap a.s.(Statoil)	Kjell A. Anfinsen	Telephone Fax	(+47) 51 87 62 26 (+47) 51 55 15 71
Amoco Norway Oil Company (Amoco)	Richard Verley	Telephone Fax	(+47) 73 58 41 85 (+47) 73 96 72 86
Exxon Production Research Company (EPR)	Ole Jørgen Narvestad	Telephone Fax	(+47) 51 50 20 18 (+47) 51 50 22 18
etrobras /CENPES/DIPREX	Robert Appleby	Telephone Fax	(+1) 713 965 7193 (+1) 713 966 6423
	Adilson C. Benjamin	Telephone Fax	(+55) 21 598 6263 (+55) 21 598 6793



INTRODUCTION

2.5 Conversion Factors

SI units are used in the report. The conversion factors between SI units and US units are;

From US units to SI units

Length: 1 in (inch) Mass 1 lb (pound) Force 1 lbf (pound force) 1 kip Stress (Pressure) 1 psi (lbf/in2) 1 ksi (1000 psi)	= 0.4 = 4.4 = 4.4 = 0.0	5.40 mm 4536 kg 448 N 448 kN 906895 MPa (N/mm2) 895 Mpa
--	----------------------------------	--

From SI units to U. S units

Length:	_		
Mass	1 mm	=	0.03937 in
Force	1 kg	=	2.205 lb (pound)
	1 N	=	0.2248 lbf (pound force)
Stress (Pressure)	1 kN	=	0.2248 kip
on ess (1 ressure)	pu	=	145.0 psi (lbf/in2)
1 ksi =	I Mpa	=	0.1450 ksi
1 1/31 —	1000 psi		

1 ksi = 1000 psi 10 bar = 1 MPa



GENERAL INFORMATION OF THE MODELS AND ANALYSES

3.1 Introduction

A large number of analyses have been carried out with various pipe wall thickness and extent of corrosion defects, and different loading conditions and material properties have been applied. Approximately 100 models were generated (different pipe dimensions and corrosion defect), and the models were analysed with various loading conditions and material properties, resulting in a

Most of the models were 3D models with solid elements and full non-linear material and geometry formulation. When appropriate, as for instance this was applied for the analyses of the girth weld corrosion, 2D models were used. In this specific case axisymmetric plane solid elements were applied. Also the burst capacity of none and infinite long corrosion defect were analysed using 2D models, and in this case plane strain elements were applied.

The FE analyses were carried out using the general purposed non-linear program ABAQUS version 5.4 and 5.5, on a VAX Alpha 2100 4/275 computer. The solution time for the 2D analyses varied from a few seconds to some minutes and from 20 minutes to 15 hours for the 3D models. The total CPU time used is approximately 700 hours.

3.2 Overview of the FE models

The majority of the 3D models were generated with outer pipe diameter of 324 mm (D), with 3 different wall thickness (t), 10mm, 16mm and 22mm and various extent of corrosion defects. The models were selected to cover the following basic parameters;

• Diameter: 324 mm

 Thickness 10, 16 and 22 mm (D/t ratio of 32, 20 and 15)

 Corrosion defect depth 0.15, 0.30, 0.50 and 0.70 of the wall thickness

 Corrosion defect length 0.15, 0.25, 0.50, 0.75, 1.0, and 2.0 of the pipe diameter

For the full matrix of the pipe and defect dimensions given above, a total of 72 models were generated. Additional 3D models has been generated with deeper or wider corrosion, internal versus external corrosion, and a few models were made in order to duplicate published results in order to validate the results. The corrosion defects were rectangular shape with smooth edges. A few models with parabolic corrosion defect shape were generated.

The girth weld corrosion defects were analysed employing axisymmetric 2D models. Likewise, the effect of the corrosion defect width of longitudinal defects with infinity length was assessed using plane strain 2D models. The effect of the shape of transition between the plain pipe and the corrosion defect for infinity long corrosion were also studied, as well as the effect of various mesh densities were also studied using 2D models.

All defects assessed were single smooth shaped corrosion defects.



Selected plots of the models are show in Figure 3-3 to Figure 3-11.

3.3 Computer program

The general purpose no-linear program ABAQUS, version 5.4 and 5.5 was used.

3.4 Generation of the models

The FE element models were generated in Solvia-Pre, and the node co-ordinates, element topology, boundary conditions and pressure load were converted to ABAQUS input format by use of an in-house program. The additional input required for the analyses were edited into the ABAQUS input file, such as material properties, loading sequence etc..

3.5 Mesh and element types

For the all the 3D models the solid element C3D20R were used. This is a reduced integration order 20 noded element. In the corroded region 4 elements were used through the thickness, and at some distance away from the corroded region the number of elements were reduced to 1 element through the thickness.

For the 2D modes the solid element types CAX8R and CPE8R was used for axi-symmetric and plain strain analyses, respectively.

Typical size of a 2D model was 500 nodes and 100 elements. Number of degree of freedom (in ABAQUS noted variables) were 800, and wavefront approximately 30.

Typically for the 3D models the size of the models varied from 2500 to 8000 nodes, and from 350 to 1300 elements. Number of variables varied from 7000 to 22000, and wavefront from 250 to 600.

3.6 Boundary conditions

For the 3D models advantage of symmetry was taken, hence only 1/4 of the pipe was modelled. Symmetry boundary conditions were applied at the symmetry planes.

For the models with internal pressure and bending moment additional boundary conditions were applied at the end of the pipe, and a beam element were connected to the end to allow for application of bending moment or prescribed rotation.

3.7 Loads

Internal pressure was applied at all internal surfaces of the pipe. The axial tension due to the end cap was applied in the pipe wall at the cut-off boundary of the model simultaneously with the internal pressure. For the full non-linear analyses the surface pressure loads are also updated with updated geometry due to deformations. This is vital for the burst capacity analyses, and in case of not updating both the geometry and the loads would have given erroneous results.

Models to which bending moment were applied were made with a beam at the boundaries of the model for easy application and control of the bending moment. The axial compressive loads were applied at the cut-off boundary of the model.



3.8 Materials

The material properties were based on the results from the Superb project, giving the mean values and the distribution for the material yield and tensile strength for different materials from X60 to X80. For the purpose of the finite element analyses the material curve is required given in true stress versus true strain. In order to have a clear definition of the material a procedure to generate different materials were made. By using this procedure and the mean values from the Superb project the "average" X60 material and X80 material were generated.

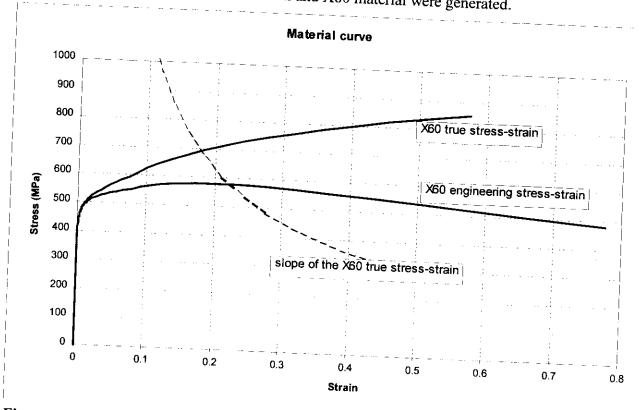


Figure 3-1 True and engineering stress strain material curve for mean X60 material

The true UTS is calculated from the maximum point at the engineering stress-strain curve, using the following expressions;

$$\begin{split} & \epsilon_{\text{true}} = \ln(1 + \epsilon_{\text{eng}}) \\ & \sigma_{\text{true}} = \sigma_{\text{eng}}(1 + \epsilon_{\text{eng}}) \end{split}$$

This is also the location where the slope of true stress-strain curve is equal to the true-stress strain curve, see figure

The sensitivity of the material properties was also studied, and sets of variations of the X60 material were generated. From the mean yield strength and the mean ultimate strength a \pm 10% variation were made, resulting in 9 combinations as listed in Table 3-1. The corresponding 9 material true-stress curves are shown in Figure 3-2



Table 3-1 X60 material variations (engineering values)

+ 10 %											
+ 10 %	mean value	- 10 %									
414	460	506									
520	578	636									
	414	414 460									

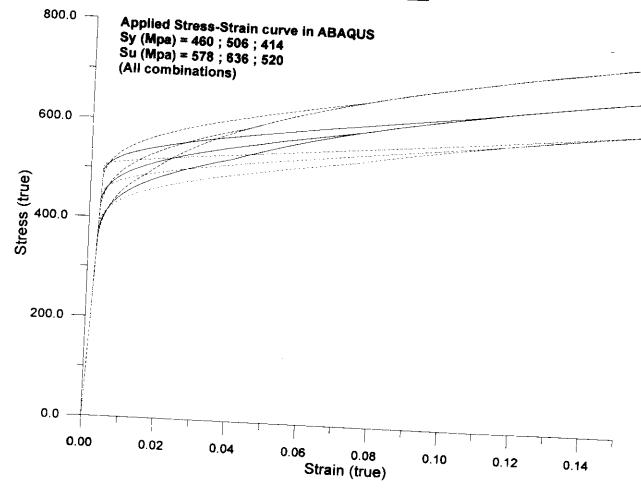


Figure 3-2 True stress-strain material curve for the X60 material sensitivity study

3.9 Solution strategies

The general purpose program ABAQUS was applied for the analyses, and both material non-linearity and non-linear geometry (large deformations) accounted for in all the analyses. In generally a static loading procedure war applied, and the loading was increased until equilibrium was not obtained for a small increment of the applied load.

In ABAQUS a arc-length type of solution strategy called the Riks algorithms is available, which will allow for analyses with an unstable behaviour. By applying this method the loading can continue also after the critical load has been reached, and the load will be decreased allowing further increased deformations. The maximum, or say critical pressure, when using the Riks



method is the same as when the static analysis procedure has become numerically unstable, no equilibrium is obtained.

3.10 Failure criteria

3.10.1 Analyses with internal pressure

The failure criterion for the analyses with applied internal pressure was adopted from the work by British Gas (Fu and Kirkwood, 1995). British Gas has supported and verified the criterion with several unpublished full scale laboratory tests.

In simple terms, burst failure occur when the whole thickness at the corrosion defect has reached UTS, the true stress level at the engineering material tensile strength. For most of the analyses, depending of the size of the corrosion defect, numerical instability occurred at a slightly higher pressure then the failure criterion used.

3.10.2 Analyses with combined loading

The same criterion as for the analyses with internal pressure was not found to be suitable for the analyses with combined loads. There is a significant difference in the local stress distribution in the area of the corrosion defect for a pipe exposed to internal pressure and combined internal pressure and axial compressive loads. For internal pressure only (with end cap), the pipe material is subjected to hoop stress in tension and an axial tensile stress which is half the hoop stress, and the loading is in one direction until failure. Numerical instability will occur at a slightly higher pressure level then the defined failure criteria.

For the case with combined internal pressure and axial compressive force the stress distribution in the area of the corrosion defect is different, and when applying one load only and keeping the other constant, the ratio between the hoop stress and the axial stress changes. And at a high level of compressive stress and a lower level of tensile hoop stress the material will not fail in the hoop direction (burst), but plastically deform. In order to obtain burst the internal pressure has to be increased, and in displacement control due to yielding this will result in reduced reacting axial force. Different failure criteria for the combined loading have been applied. Candidate failure models are for internal pressure only (reached UTS), a strain criterion, a stress criterion, or numerical instability. The latter must be used with care since instability could be caused by improper boundaries of the FE model. For modest axial load the failure criteria where the whole ligament reaches UTS could be appropriate, but for large axial loads and modest internal pressure a strain criteria could be better. In many cases the predicted capacity is not very sensitive to the failure criterion used, as far as the strain level and stress level used as the criterion is adequate. The criterion used is indicated in each case for the analyses with combined load.



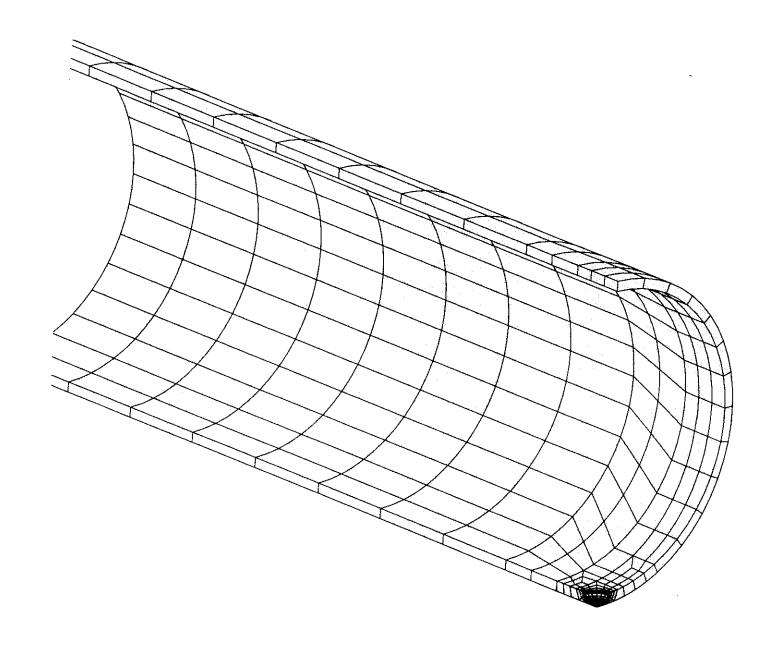


Figure 3-3 Example of typical finite element model, general view. D = 324 mm, t = 10.0 mm, d/t = 0.5, L/D = 0.15, w = 3t



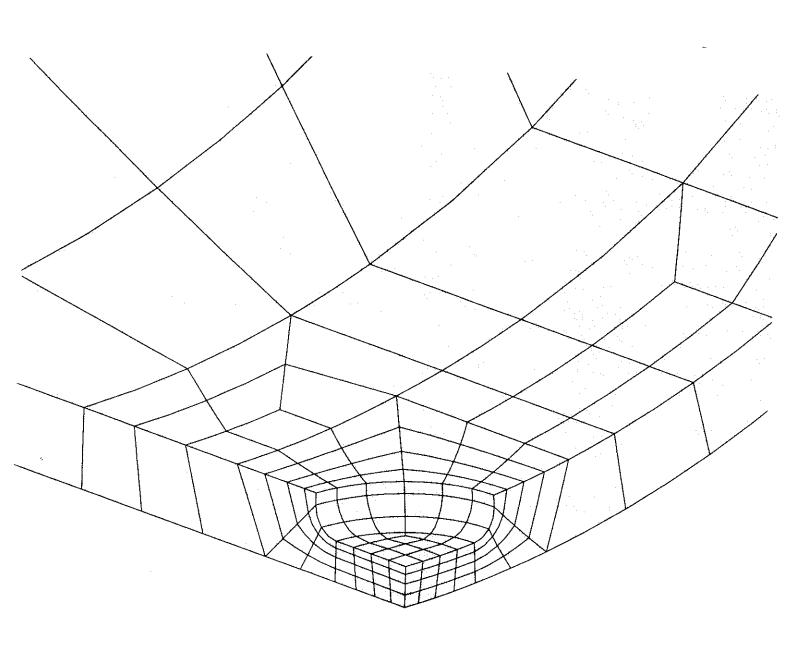


Figure 3-4 Example of typical finite element model, close-up view. D = 324 mm, t = 10.0 mm, d/t = 0.5, L/D = 0.15, w = 3t



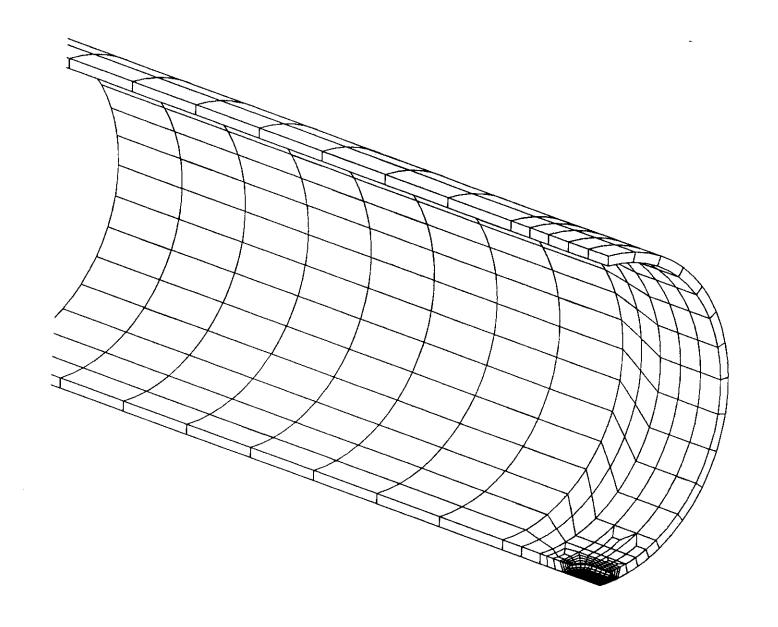


Figure 3-5 Example of typical finite element model, general view. D = 324 mm, t = 10.0 mm, d/t = 0.5, L/D = 0.25, w = 3t



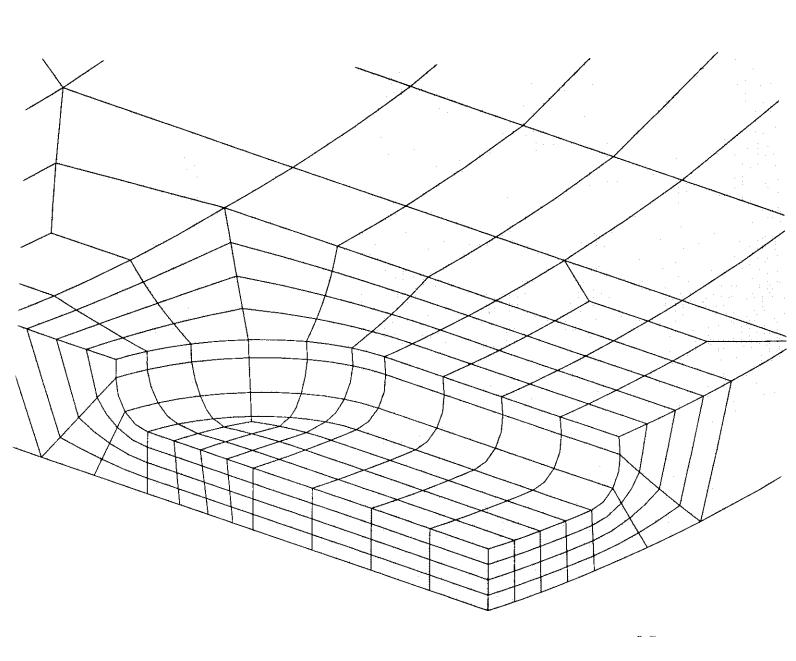


Figure 3-6 Example of typical finite element model, close-up view. D = 324 mm, t = 10.0 mm, d/t = 0.5, L/D = 0.25, w = 3t



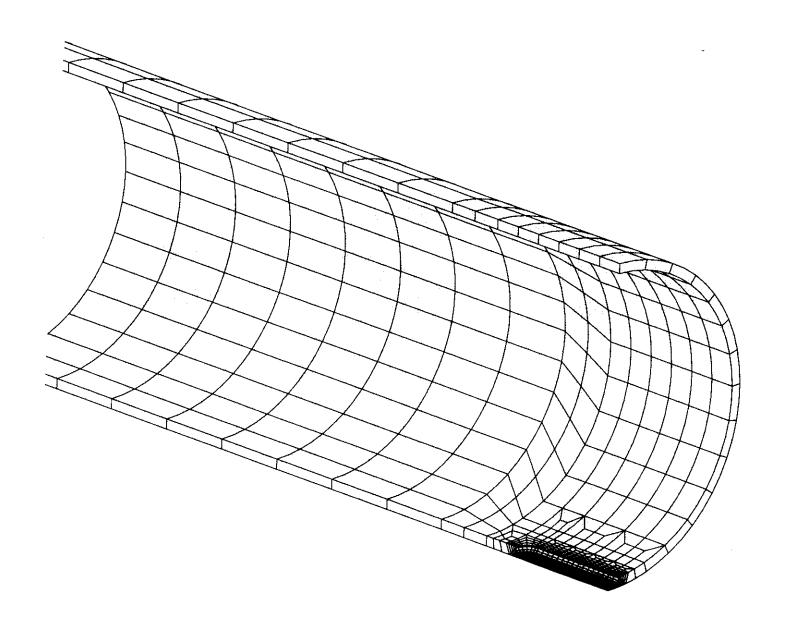


Figure 3-7 Example of typical finite element model, general view. D = 324 mm, t = 10.0 mm, d/t = 0.5, L/D = 0.75, w = 3t



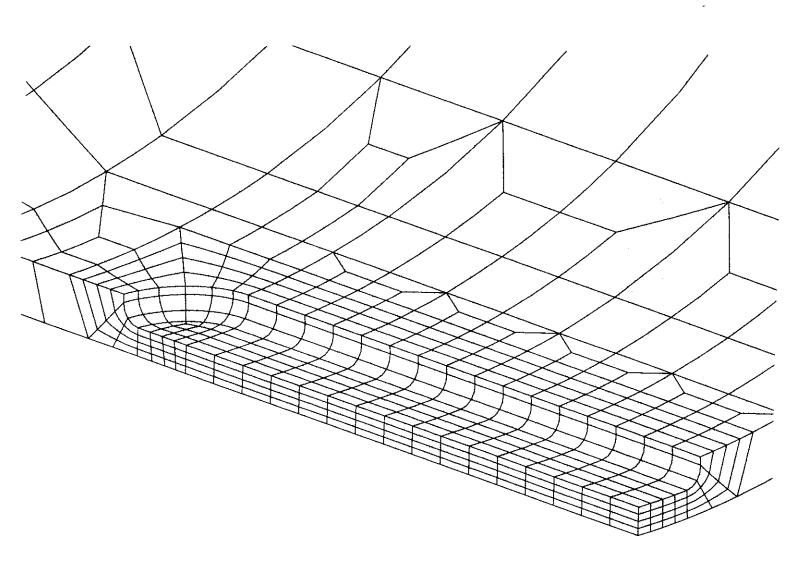


Figure 3-8 Example of typical finite element model, close-up view. D = 324 mm, t = 10.0 mm, d/t = 0.5, L/D = 0.75, w = 3t



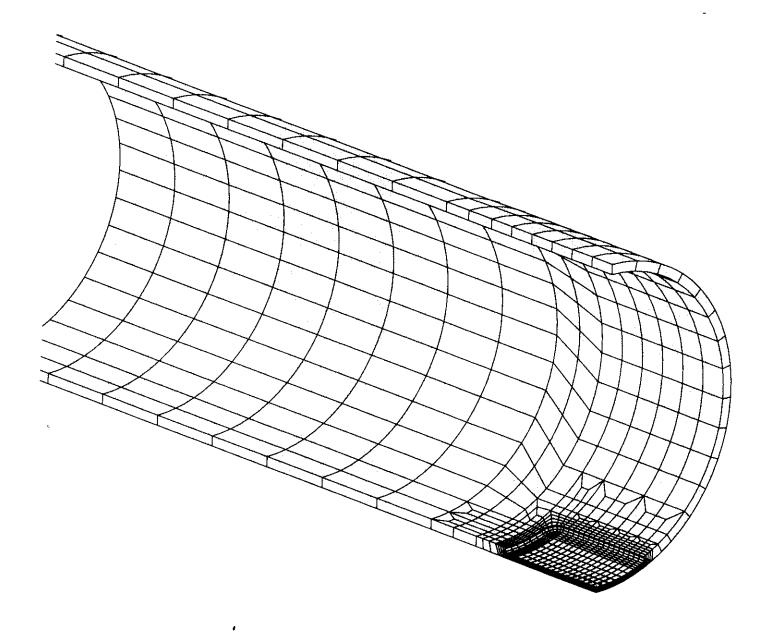


Figure 3-9 Example of typical finite element model, general view. D = 324 mm, t = 10.0 mm, d/t = 0.5, L/D = 0.75, w = 15t



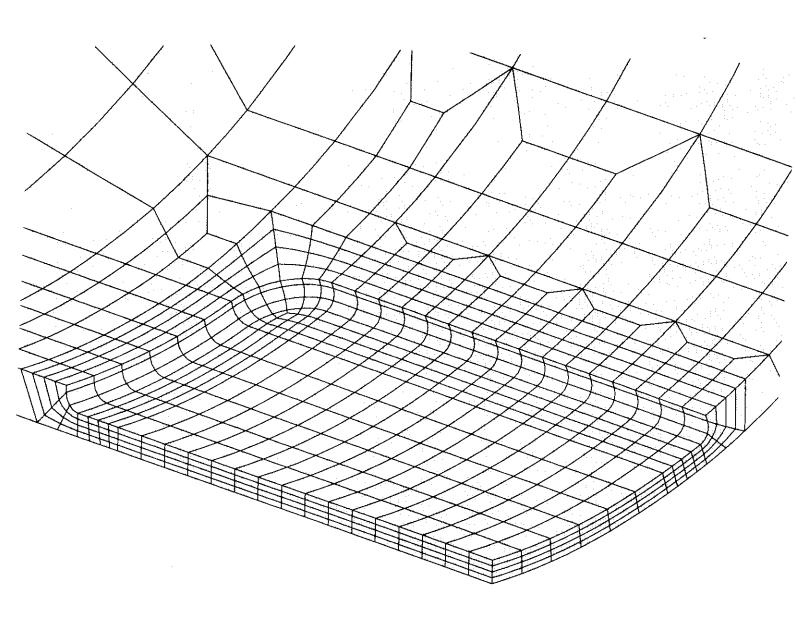


Figure 3-10 Example of typical finite element model, close-up view. D = 324 mm, t = 10.0 mm, d/t = 0.5, L/D = 0.75, w = 15t



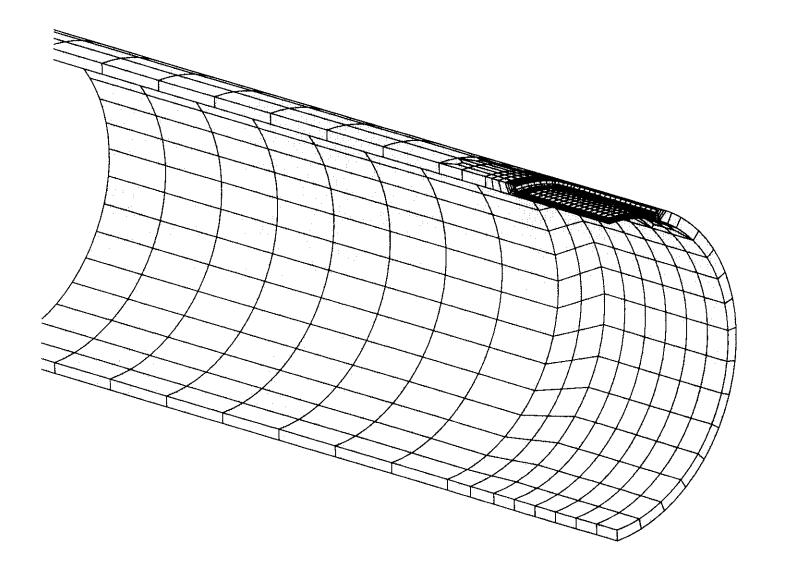


Figure 3-11 Example of typical finite element model, general view. D = 324 mm, t = 10.0 mm, d/t = 0.5, L/D = 0.75, w = 15t, outside corrosion defect



4 LONGITUDINAL CORROSION DEFECTS, INTERNAL PRESSURE

4.1 3D analyses

4.1.1 Corrosion depth and length sensitivity

A series of analyses were performed with internal pressure with smooth rectangular shaped corrosion defects with various length and depth, and both the X60 and the X80 material were used. The results are shown in Figure 4-1 for the analyses with X60 material, and in Figure 4-2 for the analyses with X80 material. The capacity equation developed within this project is based upon these results for the corrosion defect length and depth parameters. The results are normalised to P_0 , which is defined as

$$P_0 = \frac{2 \cdot t}{D - t} \cdot \sigma_u \tag{4.1}$$

σ_u : ultimate tensile strength
 t : pipe wall thickness
 D : pipe outer diameter

The results are given in tabular form in the next pages.

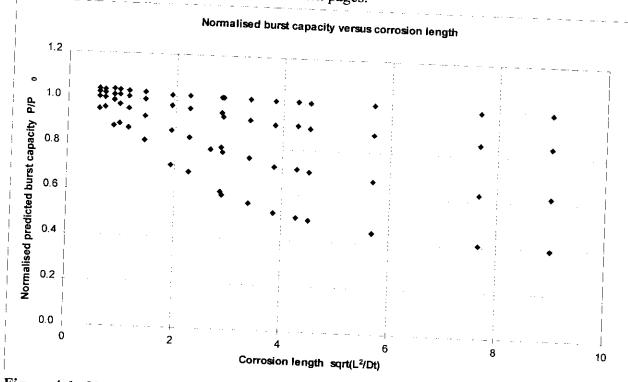


Figure 4-1 Normalised burst capacity, X60 material



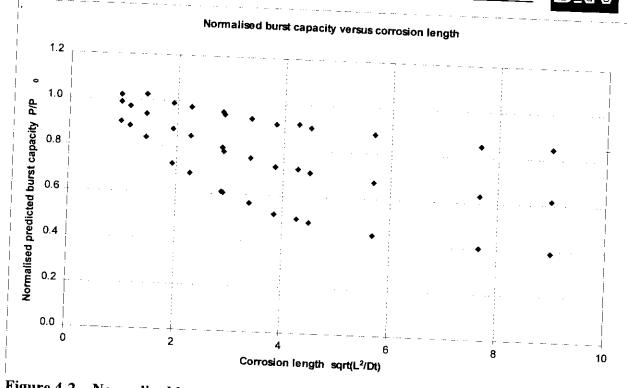


Figure 4-2 Normalised burst capacity, X80 material



[====	mm	mm	mm	mm	T	T		T			т					
ID	Dia	<u> </u>	L	= = =	w/t	Dia/t	L/Dia	+=,=	<u> </u>	±:=-=	MPa	MPa		bar	bar	Τ
DANK OVE					 ''''	Dia/t	L/Dia	d/t	sqrt(L2/(L	i Shape	Yield	UTS	Material	<u></u>	PC	
DNV-\$43	_ 324	10		1.5	3	32.4	0.15	15 %		- 	ļ		ļ —	 -		PC
DNV-S44	324	10	81.0	1.5		32.4	0.25				460	578	X60mm	368.	2 - 383	í ;
DNV-S45	324	10	162.0	1.5		32.4	$-\frac{0.23}{0.5}$	+	$-\frac{1.42}{1.42}$		460	578	X60mm	368.		+
DNV-S46	324	10	243.0	i.5	1_	32.4	0.75		2.85		460	578	X60mm	368.		÷
DNV-S47	324	10	324.0	1.5	.1.	32.4		15 %	4.27		460	578	X60mm	368.	- 	+
DNV-S48	324	to	648.0	1.5	1 "	32.4	1	15 %	5.69	rect.	460	578	X60mm	368.		+ ·
DNV-P1	324	10	1500.0				2.	15 %	11.38	rect.	460	578	X60mm	1		+ -··· -
DNV-S16	324	- 10		1.5	- 3	_ 32.4	4.63	15 %	26.35	rect.	460	4		368,2		_0
DNV-517	324	- 10	- 48.6	3	3	32.4	0.15	30 %	0.85	rect.	460		X60mm	368.2	+	0
DNV-518	324	$-\frac{10}{10}$	81.0	3	3	32.4	0.25	30 %	${1.42}$	rect.	460		X60mm	368.2	374	1
DNV-S19	324	L.	162.0	3	3 1	32.4	0.5	30 %	2.85	rect.		578	X60mm	368.2	368	1.
DNV-S20	L	10	243.0	3	3	32.4	0.75	30 %	4.27		460		X60mm	368.2	350	0.
DNV-834	$\frac{324}{324}$	_ [0]	324.0	3	3	32.4		- 3 0%	5.69	rect.	_ 460		X60mm	368.2	333	0.
DNV-934 DNV-P2	324	<u>1</u> 0	648.0	3	3	32,4		30 %	11.38	rect.	460	578	X60mm	368.2		$-\frac{0}{0}$
And the second second	324	10	1500.0	3	3	32.4	4.63	30 %		rect.	460	578	X60mm	368.2		0:
DNV S21	324	. 10	48.6	5	3	32.4	0.15	50 %	26.35	rect.	460	578	X60mm	368.2		
DNV-S22	324	10	81.0	5	3 +	32.4	0.25		0.85	rect.	460	578	X60mm	368.2		_ 0.
DNV-S23	324	10	162.0		-3-1	$-\frac{32.4}{32.4}$		50 %	1.42	rect.	460	578 3	X60mm	100 mm 1 mm		0.9
DNV-S24	324	10	243.0	[-	-3-1		0,5∏	50 %	2.85	rect.	460	578 3	(60mm	368.2		0,9
DNV-S25	324	10	324.0	5	$\frac{3}{3}$	32.4	0.75	50 %	4.27	rect.	460	578	(60mm	368.2	293.6	_ 0.7
ONV-S35	324		648.0	1-		32.4	1	50 %	5.69	rect.	460	70	K60mm	368.2	263.4	0.7
DNV-P3	324		500.0	5	3	32.4	2.	50 %	11.38	rect.	460			368.2	247.7	0.6
DNV-S26	324	10	48.6	5	3	32.4	4.63	50 %	26.35	rect.	460		(60mm	368.2	223.5	0.6
NV-S27	$-\frac{324}{324}$ -	- 10		4	3	32,4	0.15	70 %	- 0.85	rect.	$-\frac{460}{460}$	- 2/8 X	(60mm	368.2	216.5	0,5
NV-S28	$-\frac{324}{324}$		81.0	· · —	3	32.4	0.25	70 %	$-\frac{1.33}{1.42}$	rect.	+	- 3/8/X	60mm	368.2	324	0.8
NV-S29	$-\frac{324}{324}$	_ + .	162.0		3	32.4	0.5	70 %		rect.	460	578 X		368.2	301.8	0.8
NV-S30	• 1		243.0		3	32.4	0.75	70 %	:-:		460		60mm	368.2	223.3	0,6
NV-S36	324	- + -	324,0		3	32.4		70 %		rect.	- 460	578 X	60ının	368.2	185.2	0.5
NV-P4	324		648.0	7	3	32.4	- 2 -	70 %		rect.	460	578 X	60mm	368.2	164.8	0,44
NV-S37	324		500.0	7	3	32.4	4.63	70 %		rect,	460	578 X	60mm	368.2	137.6	0.3
NV-537 NV-538	324	16	48.6	2.4	3	20.25		15 % -		rect.	460	578 X	60mm	368.2	129.8	0.3 0.3
	324	16	81.0	2.4		20.25		15 %		rect.	460	578 X	50mm	600.5	623	
NV-S39	324	16 1	62.0	2.4	+	20.25				rect.	460	578 X		600.5	621	1.03
NV-S40	324	16 2	43.0			0.25		15 %		rect.	460	_ 578 X6	Omm	600.5	i	1.03
NV-S41	324	16 3	24.0		-4	0.25		15%	3.38	rect.	460	578 X6	Omm	600.5	612	1.01
NV-\$42	324	16 6	48.0	2.4		0.25		15 %		rect.	460	578 X6	0mm	600.5	608	1.01
NV-P6	324	** **	00.0	2.4 3	4			15 %	9.00	ect.	460	578 X6	Omes		604.1	1,00
NV-S1	324		48.6	4.8 3				15 %	20.83 r	ect.	460	578 X6	O	600.5	594.5	0.99
VV-S2	324		81.0	4.8 3		그런 부드 시		30 %	0.68 r	ect.	460	578 X6	0	600.5	591.2	0.98
1V-S3	324	4 .	62.0		- I			0 %		ect.	460			600.5	616	1.02
IV-S4	324	4	13.0	4.8 3 4.8 3	- 1	0.25		0 %	2.25 r	ect.	460	* * 4	0mm	600.5	606	1.00
IV-S5	324	L. T.	24.0	1 -				0 %		ect.	460	570 701	0mm	600.5	578	0.96
IV-S32	T 21		8.0	4.8 3	L	0.25	1 3	0 %		ect.	460	578 X60	Omm	600.5	553,7	0.922
IV-P7	the grant and the			4.8 3	-4	0.25	2. 3	0 %		ect.	460	578 X60	Jmm	600.5	537.1	0.894
V-S6				4.8 3			1.63 3	0 %		ect.		578 X60)mm	600.5	505.7	0.842
V-S7	and the second		8.6	8 3	20	0.25).15 5	0%		ect	460	578 X60	mm	600.5		0.820
V-S8		- + -	1.0	8 3	20			0 %			460	578 X60	mm T	600.5	· ·	1.002
v-59			2.0	8 3	20	.25	· +	0 %	3.25	ct.	460	578 X60	mm_	600.5	******	0.958
V-S10			3.0	8 3	-		-+-			ct.	460	578 X60	mm	600.5		0.838
			4.0	8 3	4	.25	· i— —	 	7	ct	460	578 X60	mm	600.5		0.756
V-S32_2		64	<u>.</u> .	8 3		25			4.50 re	1	460	578 X60	mm	600.5	,	0.736 0.704
V-P8		6 150	0.0	8 3		- +		- +	9.00 re		460	578 X60	mm -	600.5		
		6 190	0.5	3.0 3	+	.25 0.5			20.83 re	ct.	460	578 X60		600.5		0.621
V-S11	324 1	+	- + 1	.2 3	20			%	2.65 re	ct.	460	578 X601	1	600.5).586
		6 8		2 3	20			%	0.68 rec	ct.	460	578 X601	t	·		789
/-S13	- t-	6 162		$\frac{2}{2} = \frac{3}{3}$	+			%	1.13 rec	ct. -	460	578 X60r		600,5		959
/-S14	324			I	20.		- +	%	2.25 rec	i. 7 – -	460	578 X60r			· · - · · · · · · · · · · · · · · · · ·	.873
/-S15	324				$-\frac{20}{20}$			%	3.38 rec		460	578 X60n				.685
100 mm s	324 - I				_20.	· - i	1 70		4.50 rec	- 4	460	578 X60n				.561
	324		- +		20.	: +	2. 70	%	9.00 rec		460	- 10 ADUN		500.5		.492
	$\frac{324}{324} - \frac{10}{23}$		— — · · · · ·		_ 20				20.83 rec		460	578 X60n				.392
	$\frac{324}{324} - \frac{24}{22}$				14.7			%	0.58 rec	+	460	578 X60n	· - · · - · · - ·	500.5	211 0	.351
		-1			14.72				0.96 rec	·	400	578 X60m	nm 8	42.1		041
· = I					14.72	7 0	.5 15				460	578 X60m	ım 8	42.1		039
	324 22		_f		14.72					-+	460	78 X60m	ım 8	42.1		021
E.E	324 - 22			3 3	14.72		1 15			+	460	78 X60m	ım 8	42.1		015
2007	22	4	0 3.	1	14.72		2. 15		3.84 rect		460	78 X60m		42.1		
	24 22				14.72	· +			7.68 rect		460 5	78 X60m	+			009
	24 _ 22			+	14.72	–⊢ –∷			7.77 rect		160 - 5	78 X60m		· + · · · · ·		990
	24 22		_1	-t	14.72				0.58 rect			78 X60m		42.1 - 8 42.1 - 8		982
S57 3	24 22			4				·+	0.96 rect			78 X60m				026
			<u> </u>		14.72	7 0.	5 30 9	6	.92 rect.			78 X60m	1 84	12.1	856 1.0	016



T = E = -	mm = = =	mm	mm	mm	1						7 7 -					
ID	Dia	τ	L	d	w/t	Dia/t	L/Dia	= <u>=</u> =	===	===	MPa = = =	_MPa		bar	bar	T
DNV-\$101			i		1		DiDia	u/t	sqrt(L2/()	Di Shape	Yield	UTS	Material	P0	F _{PC} =	PC/P
DNV-S101	324	10		3	3	32.4	0.25	30 %	1.4	<u>.</u>				 	 	10/1
DNV-S102 DNV-S103	324	10	-	3	3	32.4	0.5				601	727	X80mm	463.		$-\frac{1}{1.0}$
DNV-S103 DNV-S104	324	10	243.0	3	3	32.4	0.75		2.8	_	601	727	X80mm	463.		1
	324	_10	324.0	·· ·· 3	3	32,4	1	, .	4.2	+	601	727	X80mm	463.1		
DNV-S105	324	10	648.0	3	3	32.4	2.1	, .	5.6	- t	100		X80mm	463.1	1	1 011
DNV-S91	324	10	81.0		3 - [32.4	0.25	/ •	11.38		601	727	X80mm	463.1	386.3	1
DNV-S92	324	10	162.0	5	3-	32.4	0.23	50 %	1.42		601	727	X80mm	463.1	435,9	
DNV-S93	324	10	243.0	5	3	32.4		50 %	2.85		601	727	X80mm	463.1	+	1 117
DNV-S94	324	10	324.0	· · · · · · · · · · · · · · · · · ·	3	32.4	0.75	50 %	4.27		601		X80mm	463.1	$-\frac{372.6}{322.6}$	0.8
DNV-S95	324	10		5	31	1	1	50 %	5.69	rect	601	727	X80mm		333.8	0.7
DNV-S96	324		81.0	7	3	32.4	2.	50 %	11.38	rect	601	727	X80mm	_ 463.1	312.2	0.6
DNV-S97	324	10	162.0	/	- 3- -	32.4	0.25	70 %	1.42	rect.	- 601	757	X80mm	_ 463.1	280.7	0.60
DNV-S98	324	101	243.0			32.4	0.5	70 %	2.85	rect	601	727	X80mm	463.1	388	0.83
DNV-S99	324	10	324.0		3	32.4	0.75	70 %	4.27	rect.	601	72/1	180mm	463,1	282.3	0.6
DNV-S100	324	10	648.0	$-\frac{7}{7}$	3	32.4	1 t	70 %	5.69	rect.	601	/2/ / 72/ /	K80mm	463.1	231.6	0.50
DNV-S107	324	16			3	32.4	2.	70 %	11.38	rect	601	- 727 2	(80mm	463.1	205.3	0.44
NV-S108	324	16	162.0	_ 4.8	3	20.25	0.5	30 %	2.25	rect.		- /27 }	(80mm	463.1	171.9	0.37
NV-S109	$-\frac{324}{324}$		243.0	4.8	3	20.25	0.75	30 %	3.38	rect.	601		(80mm	755.3	737.9	0.97
NV-SI 10	324	16	324.0	_ 4.8	3	20.25	ī	30 %	4.50	rect.	601	727 3	(80mm	755.3	705.1	0.93
NV-S111 -		16	648.0	_4.8	3	20.25	2	30 %	1.30		<u>601</u>] .	727 X	(80mm	755.3	681.3	0.90
NV-SI 12	324	16	81.0	8	3	20.25	0.25	50 %		rect.	601	727 X	80mm	755.3	637.4	0.84
	324	_16	162.0	8		20.25	0.5	50 %	$-\frac{1.13}{2.25}$	rect.	601	727 X	80mm	755.3	735,4	0.97
NV-S113	324	16	243.0	8		20.25	0.75	50 %	1	rect.	601	727 X	80mm	755.3	640.9	0.84
NV-SI 14	324	16	324.0	8		20.25	1 -	50 %	3.38	rect.	601	727 X	80mm	755.3	574.5	0.76
NV-S115	324	16	648.0	- 8		20.25	<u>-</u>	50 %	- 4.50	rect.	601	727 X	80mm	755.3	532.7	
	324	161	81.0			20.25	0.25	1	9.00	rect.	601	727 X		755.3	467.4	0.705
	324	16	162.0			20.25	0.23	70 %	1.13	rect.	601	727 X		755.3		0.619
	324		243.0	L.	- · I	20.25	1 _	70 %	2.25	rect.	601	727 X	ROmm	- 755.3 - 755.3	670.9	0.888
	324		324.0	-		20.25	0.75	70 %	3.38	rect.	601	727 X		755.3	520	0.688
VV-S120	324		648.0					70 %	4.50	rect.	601	727 X			427.5	0.566
V-S86	324	22	81.0			20 25	+-	70 %	9.00	rect.	601	727 X8	ON THE PARTY OF TH	755.3	369.1	0.489
77	324 i		162.0			.727		30 %	0.96	rect,	601	727 X8	oumm — I -	755.3	293.2	0.388
773 674	∷↓ 324		243.0			.727		30 %		rect.	601	727 340		1059.2	1080	1.020
23	324 324		324.0	6.6	- [- ``	727	0.75	30 %	2.88	rect.	601	727 X8	Omm_	1059.2	1048.4	0.990
	324	1 .		6.6		.727	tí :	30 %	3.84	rect.	601	727 X8	0mm	1059.2	1002.2	0.946
	324	$\frac{22}{22}$	648.0 ¹	6,6		.727	2. :	30 %		rect.	601	727 X8		1059.2	968.1	0.914
	324 324		81.0	[1] 3	1	.727		50 %	12. 21. 3	rect.		727 X8		1059.2	901	0.851
		. 4	62.0	_ 11 _3		.727		50 %		rect.	601	727 X8		1059.2	1047.6	0.989
	- 4	4	43.0	11 3		727	- 1 .	50 %i	··· = ·		601	727 X8		1059.2	928.2	0.876
	4	1.1	24.0	11 3	14.	727		50 % 1	Ta ta . #*	rect.	601	727 X80		1059.2	832.8	0.786
. 200 4 .7	- 1		48.0	11 3	14.	727		0 % -		rect	103	727 X80	Omm -	1059.2	770.9	0.728
	- +		81.0	5.4 3	40 0 0			0 %		rect	601	727 X80		1059.2	667.9	
			62.0 j	5.4 3		727] 727]	· · · ·			ect.	601	727 X80		1059.2	960.3	0.631
	24	22Ť Ž		5.4 3	14.		·· '	0 %		ect.	601	727 X80		1059.2	769.7	0.907
				5.4 3	14.	J.		0%		ect.	601	727 X80		1059.2		0.727
V-S85 3	24			5.4 3	14.	1		0 %		ect.	601	727 X80		1059.2		0.607
				ر اد	1 14.	14/1	2. 7	0 %	7.68 r	ect	-601+ -	727 X80		103Y.Z	550.4	0.520

4.1.2 Material sensitivity, variations of the average X60 material

A few models were selected for a study of the sensitivity to variations of the material. The material yield strength and tensile strength were varied with $\pm 10\%$ which resulted in 3 levels of yield strength and 3 levels of tensile strength, a total of 9 combinations, see section 3.8. Some of the combination can seem odd and may not be a realistic material, but it is considered to be appropriate for the sensitivity study. The analysis id and the material label include 2 letters, where the first indicate the yield stress and the second one indicate the ultimate stress, where m is "mean" u is "upper 10%, and I is lower 10%.



The results of the analyses are shown in Figure 4-3 and in Table 4-1. The results grouped together are calculated burst capacities for combinations of the material using the same FE geometry model.

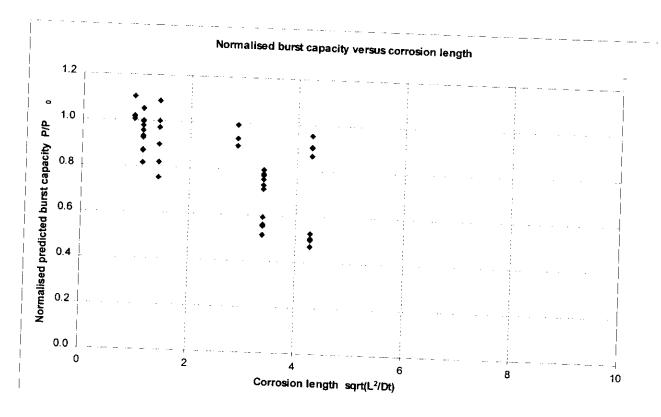


Figure 4-3 Results of the material sensitivity study



Table 4-1 Results of the material sensitivity study

No.	ho-				_	L.		Τ	Pa	MP	1Pa	M						_	÷	. : ==:		T = -		+ -			1	hi -	l n	ID
DNV-S17	barbar	bar	baı	_ ba	_		= - -	+ = -		±: = -		t==	hane	±. Di∫Si	 L2/(sqri	d/t)ia	L/D	Dia/t	1 D	w/t	<u>d</u>		L	Щ	+ 1	na	- -''	110
DSV-ST710	PO PC	PC	PC	Po	_	P0	rial	Mater	IZ	UT	leia	111	парс	- 3	· (45.753 1									·		<u> </u>	224		V-S17
DNV.STP 1							_ 1_			J	460		ent	5	1.4	ļ · ··-	30 9	.25	0.	32.4	1	3	3				4	_	. - 3	V-\$17
DNV-S1710	368.2 368	36	2 3	2	8.2	368	m _	X60mn	578	``				_+ -		† -		25	0.	32.4		3	_ 3				1		***	V-51744 V-5171
DNV-S171	405.1 405	40	$I_1^{\dagger} = 4$	11 -	5,1	405		X60uu	636	1	·			_+ -		†		1	+ -	32.4			3				i			V-817UI V ELTI
DNV-S19	331.2 360.6	360.	361	2 36	1.2	331.		X60ul	520	! <u></u>	4	ļ		27		ĺ -				32.4	1	3	3				1 .		2.0	
DNV-S19					5.1	405.					d							!.		32.4	1	3	3	1	and the same					
DNV-S19tu 324 10					ĭ.2	331.	- 1						1	! :-					+	32.4	1 :	3	3	Ţ	243.0	10	1			
INV-Sylut 324 10 2450 3 5 524 0.75 30 6 4.7 rect 506 636 800 405 365 365 300 800 31 31 31 31 31 31 31	· - +1.		+	+	š.2†	368.	n	X60mm	578	5								- 1	t			3	- 3	1 -	243.0	10	1			V-S19uu
DNV-S191 324 10 243 0 3 3 324 0 7 3 34 10 243 0 3 3 324 0 7 3 34 10 243 0 3 3 324 0 7 3 34 10 243 0 3 3 324 0 7 3 34 10 243 0 3 3 324 0 25 70 5 142 rect. 414 535 \$50 \$60 131 12 316.3 310 314 10 810 7 3 324 0 25 70 5 142 rect. 414 536 \$50 \$60 311 2 329 310 314 10 810 7 3 324 0 25 70 5 142 rect. 400 578 \$60 30 312 318 318 324 10 314 10 810 7 3 324 0 25 70 5 142 rect. 414 536 \$60 311 2 318	· + - = 1 1.		← :- :-	- 	_ 1		_ <u>_</u>	X60uu	636	6	506		ct.								·		~ 3 1	ļ.—·	243.0	ΙO	Ī	24	32	V-S19ul
DNN-S27 10											506	:	ct.					:	۰	1			- 3	í	243.0	ΪO	ī	24	32	
DNN-S27			+	+·	· . 🎞 .						414		ct.								· · · · · ·		-3	+ · ·	243.0	0	Ī	24 j	32	V-S1911
DNY-SZPU					- 4						414		ct.	7 re	4.2			- 4-			1		- 7			ΙσŤ		24^{\dagger}_{1}	32	
DANY-SZ710	= = ::::		1	-1	!		; 				460		ct.					- 1.					- 4			101	10	24	32	/-S27uu
DNV-S271u 324 10	1 1 1				1		^ —} ·-				506	٠ خ	ct.	re	1.42			Ι.					· ქ		1			24	32	/-S27ul
DNV-SZPI			t									1997 49	ct.	rec	1.42			1.								_		- 4		/-S27lu
DDW-S29u	·												et f	rec	1.42		70 %					1	-41-					- 1		
DNV-SZ9iu 324 10 243.0 7 3 32.4 0.75 70 % 4.27 rect 400 578 K60mm 330.2 271.6 DNV-SZ9iu 324 10 243.0 7 3 32.4 0.75 70 % 4.27 rect 506 6.66 K60uu 405.1 202 DNV-SZ9ii 324 10 243.0 7 3 32.4 0.75 70 % 4.27 rect 506 6.66 K60uu 405.1 202 DNV-SZ9ii 324 10 243.0 7 3 32.4 0.75 70 % 4.27 rect 506 50.5 X60ul 331.2 174.7 DNV-SZ9ii 324 10 243.0 7 3 32.4 0.75 70 % 4.27 rect 414 502 X60il 331.2 174.7 DNV-SZ9ii 324 16 81.0 8 3 20.25 0.25 50 % 1.31 rect 400 578 K60mm 600.5 575.1 DNV-SZ9ii 324 16 81.0 8 3 20.25 0.25 50 % 1.31 rect 400 508 X60iu 600.8 165.1 DNV-SZ9ii 324 16 81.0 8 3 20.25 0.25 50 % 1.31 rect 400 508 X60iu 600.8 165.1 DNV-SZ9ii 324 16 81.0 8 3 20.25 0.25 50 % 1.31 rect 400 508 X60iu 660.8 615.1 DNV-SZ9ii 324 16 81.0 8 3 20.25 0.25 50 % 1.31 rect 506 6.63 K60iu 660.8 615.1 DNV-SZ9ii 324 16 81.0 8 3 20.25 0.25 50 % 1.31 rect 506 6.63 K60iu 660.8 615.1 DNV-SZ9ii 324 16 81.0 8 3 20.25 0.25 50 % 1.31 rect 506 6.63 K60iu 660.8 611.1 DNV-SZ9ii 324 16 81.0 8 3 20.25 0.25 50 % 1.31 rect 506 6.63 K60iu 660.8 611.1 DNV-SZ9ii 324 16 81.0 8 3 20.25 0.25 50 % 1.31 rect 506 6.63 K60iu 660.8 507.5 NNV-SZ0ii 324 16 81.0 8 3 20.25 0.25 50 % 1.31 rect 506 6.63 K60iu 660.8 507.5 NNV-SZ0ii 324 16 81.0 8 3 20.25 0.25 50 % 1.33 rect 414 578 K60iii 600.5 S50.1 NNV-SZ0ii 324 16 81.0 8 3 20.25 0.25 50 % 1.33 rect 414 578 K60iii 600.5 S50.1 NNV-SZ0ii 324 16 81.0 8 3 20.25 0.25 50 % 1.33 rect 414 578 K60iii 600.5 S50.1 NNV-SZ0iii 324 16 81.0 8 3 20.25 0.75 50 % 3.38 rect 460 520 K60ii 540.3 \$40.3 \$50.9 NNV-SZ0ii 324 16 243.0 8 3 20.25 0.75 50 % 3.38 rect 460 520 K60ii 540.3 \$40.3 \$40.3 \$80.9 NNV-SZ0ii 324 16 243.0 8 3 20.25 0.75 50 % 3.38 rect 460 520 K60ii 540.3 \$		305	30	1 -	_1						- i -				1.42		70 %	5	0.2	1			- 71			· 1		i		A Company
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4.1.3 Parabolic shaped corrosion defect

A few models with parabolic shaped corrosion defect were generated, and analysed with internal pressure loading. The result shows an increase in burst capacity, see Figure 4-4. The upper line is the results for the 4 models with parabolic shaped corrosion defect, and the corresponding analyses with rectangular shaped corrosion defect are shown in the lower line. An example of the models is shown in Figure 4-5. An attempt was made to generate a number of models with parabolic shaped corrosion defect in a simple manner using one basic model and change the co-ordinates by use of a small software routine. Nice looking shaped corrosion defects were generated, but the elements at the edges of the corrosion defects did not show convincing behaviour, and hence the results from the analyses are not included in the report.

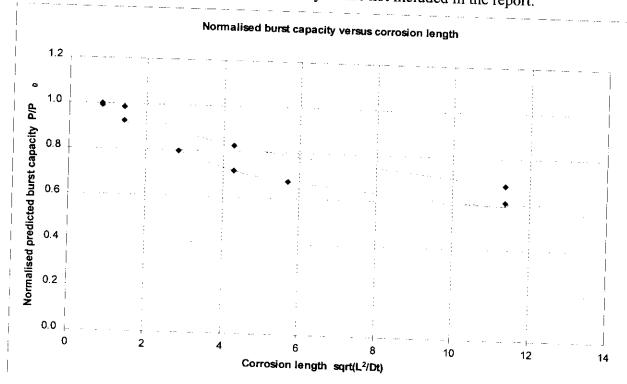


Figure 4-4 Parabolic shaped corrosion (parabolic upper line, rectangular lower line)

Table 4-2 Results for the analyses with parabolic shaped corrosion (4 last rows)

	mm	mm	mm	mm							MD.	7.45	·			
ID	Dia	t	L	d	w/t	Dia/t	1.00:	T	= = :	<u> </u>	MPa +	MPa	!	bar	bar	
						Dia/t	L/Dia	d/t	sqrt(L2/(Di	Shape	Yield	UTS	Material	PO	PC	PC/PC
NV-S21	324	10	48.6	··· ·- 5	3 "	32.4	0.15	50 %								10/10
NV-S22	324	10	0.18	5	3	32.4	0.25	50 %	···· · ;	rect.	460		X60mm	368.2	365	0.99
NV-S23	324	10	162.0	5	3	32.4	0.5	50 %	! ** ' *=	rect.	460		X60mm	368.2	340.7	0,9
NV-S24	324	10	243.0		3	32.4	0.75	50 %	2.03	rect.	460		X60mm	368.2	293.6	0,7
NV-S25 NV-S35	324	10	324.0	5	3	32.4	- 1	50 %		rect.	460		X60mm	368.2	263.4	0,7
NV-rec10	$-\frac{324}{324}$	_ 10	648.0	5	3	32.4	! 2.¦	50 %	11.38	rect.	460		X60mm	368.2	247.7	0.6
NV-rec10	$-\frac{324}{324}$	10	48.6	5	3	32.4	0.15	50 %		parabel	$-\frac{460}{460}$		X60mm	368.2	223.5	0,60
NV-rec10	$-\frac{324}{224}$	10	81.0	5	3	32.4	0.25	50 %		parabel	460		X60mm	368.2	368	1.00
NV-rec10	$-\frac{324}{134}$	10	243.0	5	3	32.4	0.75	50 %		parabel	460		X60mm	368.2	362,5	0.98
AV-ICCIO	324	10	648.0	5	3	32.4	2	50 %		parabel	460		X60mm	368.2	304	0.82
		-									700:	3/6 .	X60mm	368.2	251	0.61



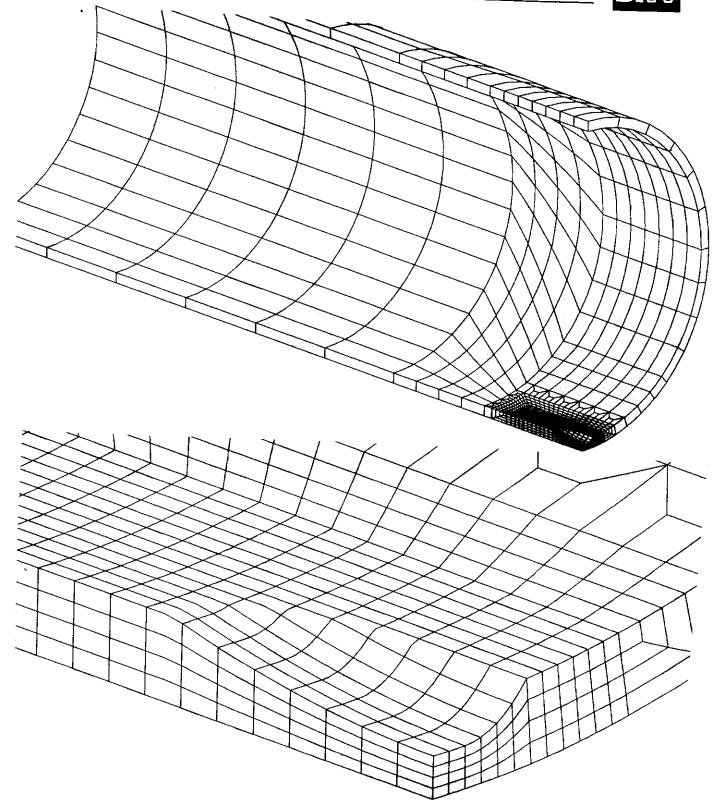


Figure 4-5 Example of model with parabolic shaped corrosion defect



4.1.4 Internal versus external located corrosion

For practical purposes the laboratory test specimens were made with the artificial corrosion defect at the outer surface. For offshore pipelines a corrosion defect is normally located at the internal surface, while for onshore pipelines the defect could as well be at the external surface. Duplicate analyses were made with the same corrosion defect at the external and the internal surface.

The burst capacities from the analyses were the same for internal and external defects.

4.1.5 Defects width

The defect width in the models was in most cases 3 times the wall thickness, but one model was made with a defect width of 15 times the thickness. The burst capacity was close to the same for the narrow and the wide defect for the X60 material. The wide defect had actually just slightly higher capacity than the narrow one.

The model, simulating laboratory test no. 1 was analysed with the material determined with coupon tests. The material curve showed a clear and long yielding plateau. Another analysis was performed to check if the yielding plateau was of significance, and the results showed close to no effect of this. The capacity was the same, even with significant change in the first part of the material curve.

Another pair of analyses were performed, same as the above, but with less width, w/t=3. In this case the same change of capacity was observed as in the sensitivity study. This effect has not been studied in more details, and it is assumed that for wide defect the capacity is mainly dependent on the ultimate strength, and for narrow defects the yield stress also has an influence. The defect length ratio was L/D=0.75 and the defect depth ratio d/t=0.50.

The defect width is studied more in detail using 2D models, which is for infinity long corrosion defects.



4.2 2D analyses

4.2.1 Infinite long corrosion

The plain strain 2D models simulates infinity long corrosion defects, and results from the analyses are shown in Figure 4-6. Infinity long corrosion defects is set equal to 1500 mm, for practical purposes, resulting in a dimensionless length of 18, 21 and 26 depending on the different wall thickness. The results from the 2D analyses correspond well with the results from the 3D analyses with long corrosion.

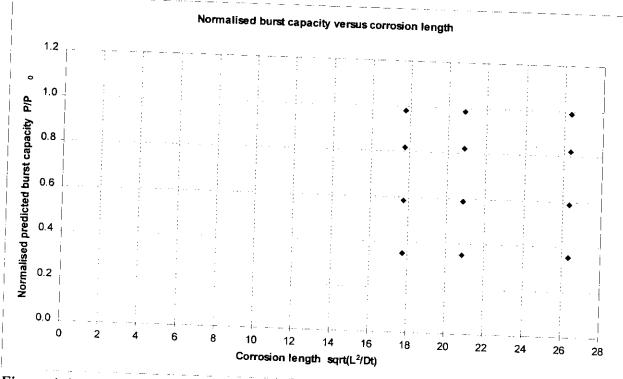


Figure 4-6 Infinity long corrosion defects, plain strain 2D analyses

Table 4-3 Infinity long corrosion defects, plain strain 2D analyses

	mm	mm				- Tallanyses											
ID -	Dia	t	L mm	mm d	 w/t	Dia/t	L/Dia	d/t	sart/I 2//D		MPa	MPa		bar	bar		
								G/ L	sqrt(L2/(Di	Shape	Yield	UTS	Material	P0	PC	PC/P	
DNV-PI DNV-P2 DNV-P3 DNV-P4 DNV-P6 DNV-P6 DNV-P8 DNV-P9 DNV-P11 DNV-P12 NV-P13 NV-P14	324 324 324 324 324 324 324 324 324 324	$ \begin{array}{c} 10 \\ 10 \\ 10 \\ 16 \\ \hline 16 \\ \hline 16 \\ \hline 22 \\ 22 \\ 22 \\ \hline 23 \\ \hline 24 \\ \hline 25 \\ \hline 30 \\ 3$	1500.0 1500.0 1500.0 1500.0	1.5 3 5 7 2.4 4.8 8 11.2 3.3 6.6 11 15.4	3 3 3 3 3 3 3 3	32.4 32.4 32.4 20.25 20.25 20.25 20.25 14.727 14.727 14.727	4.63 4.63 4.63 4.63 4.63 4.63 4.63 4.63	15 % 30 % 50 % 70 % 15 % 30 % 50 % 70 % 50 % 70 %	26.35 26.35 26.35 20.83 20.83 20.83 20.83 17.77 17.77	rect.	460 460 460 460 460 460 460 460 460 460	578 578 578 578 578 578 578 578 578 578	X60mm X60mm X60mm X60mm X60mm X60mm X60mm X60mm X60mm X60mm X60mm X60mm	368.2 368.2 368.2 368.2 600.5 600.5 600.5 842.1 842.1 842.1	363.4 302.8 216.5 129.8 591.2 492.6 352 211 827.2 688.8 492.8 296.3	0.9 0.8 0.5 0.3 0.9 0.8 0.5 0.3 0.9 0.8	



4.2.2 Corrosion width and internal versus external corrosion

The internal versus the external corrosion was also studied using 2D models.

Two models with the same dimensions as model P8 in Table 4-3 was made, but with corrosion width w/t = 9, and one with internal corrosion and the other with external corrosion. The one with internal corrosion failed at 347 bar, and the one with external corrosion failed at 342 bar, compared to the failure pressure of 352 bar for the P8 model.

The percentage difference is 1.5 % between the models with internal defect and width w/t equal to 3 and 9. There is another 1.5 % between the failure pressures for the analyses with internal defect and with external defect.

The models are included in Figure 4-7.

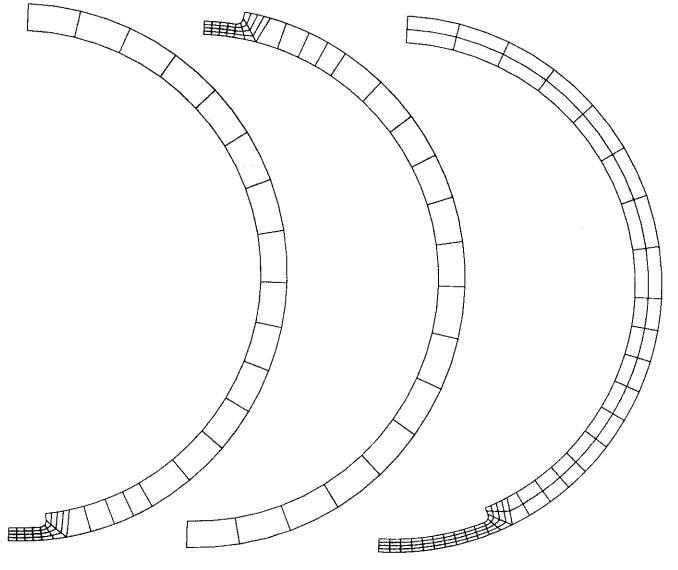


Figure 4-7 2D models, internal versus external corrosion, and width of corrosion.



4.2.3 Mesh density

In the corroded region 4 elements was used through the thickness, which was at a short distance away from the corrosion defect reduced to one element through the thickness. A model equal to the model P8, see Table 4-3 was made with finer mesh. The difference in predicted burst capacity was 0.2 bar which is negligible (and less then the assumed accuracy of the evaluation of the results). The models are included in Figure 4-8.

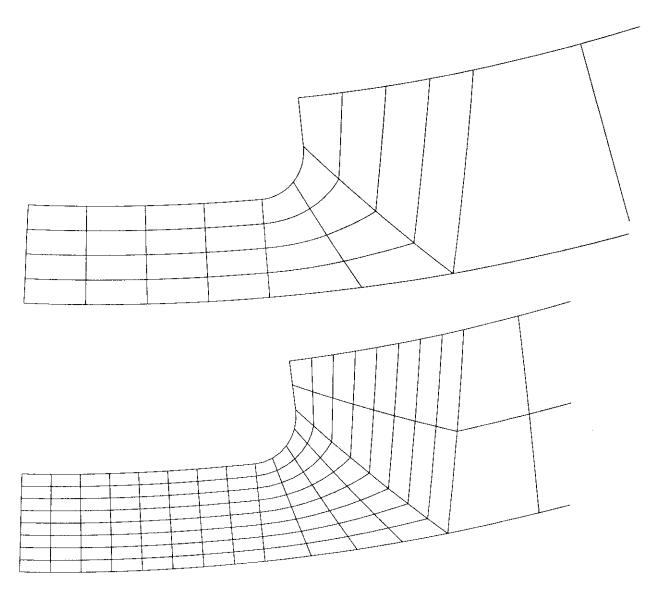


Figure 4-8 2D models, mesh density, close-up view.



LONGITUDINAL CORROSION DEFECTS, COMBINED LOADS

LONGITUDINAL CORROSION DEFECTS, COMBINED LOADS

Combined internal pressure and bending moment

Models description

Models used for the study of longitudinal corrosion with internal pressure were modified to also account for bending moment. At the boundary of the models the boundary nodes were restrained to be a stiff plate by using the *EQUATION option in ABAQUS and connect a short beam element to the stiff plate. The beam element was used to in a easy way to apply the load and boundary conditions.

5.1.2 Loading and failure criteria

First the internal pressure were applied to 165 bar, and while keeping the internal pressure constant a bending moment was applied to a predefined level. Further, no keeping the bending moment constant and the internal pressure was increased until failure. If only internal pressure was applied the models failed in the hoop direction as observed for the models with longitudinal corrosion. Three failure criteria were applied, and for high internal pressure there was a minor difference in predicted pressure, 550 MPa, 600 MPa, and numerical instability. One analysis were carried out applying rotation in stead of bending moment, allowing the bending moment to reduce when increasing the internal pressure.

5.1.3 Results

The results from the analyses are shown in Figure 5-10. The internal pressure capacity is reduced with increased bending moment. There is a difference between the various failure criteria, especially when the bending moment increases. The corroded section was located at the compressive side of the bending moment. The load path for one analysis are included, which show the resulting bending moment from an analyses in load displacement control in regard of the rotation/bending moment (always load control for the internal pressure). When increasing the pressure and holding the rotation constant, the bending moment drops. The resulting load path almost overlaps the results from the analyses with the 600 MPa criterion.

The results are compared with results from laboratory tests, and the bending moment capacity and stiffness is much higher in the analyses compared to the tests. The reason for this has not been found. Both the test results and the analyses have been checked, but no full explanation has been found. However, based on our evaluation the results from the laboratory tests seem to be the most correct, and we assume no errors in the instrument recordings in the laboratory tests.



LONGITUDINAL CORROSION DEFECTS, COMBINED LOADS

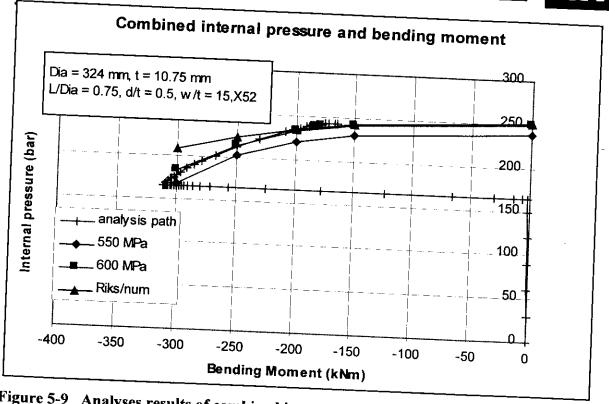


Figure 5-9 Analyses results of combined internal pressure and bending moment.

5.2 Combined internal pressure and axial compressive force

5.2.1 Models description

Models used for the study of longitudinal corrosion with internal pressure were modified to also account for axial compressive force.

5.3 Loading and failure criteria

First the internal pressure were applied to a defined level, and while keeping the internal pressure constant an axial compressive force was applied until failure. If only internal pressure was applied the models failed in the hoop direction as observed for the models with longitudinal corrosion. The burst failure was not observed in the analyses when the internal pressure was at a modest level. When applying axial compressive force this resulted in excessive plastic deformations, without indications on the pipe would have bursted. Three failure criteria were applied, and for high internal pressure there was a minor difference in predicted pressure, 10% strain, stress at UTS and numerical instability. For modest internal pressure and high axial compressive loads the numerical instability was reached before the two other failure criteria were fulfilled. A tensile failure, rupture, was not predicted for modest internal pressure, only excessive yielding was observed.



LONGITUDINAL CORROSION DEFECTS, COMBINED LOADS

5.4 Results

The results from the analyses are shown in Figure 5-10. The internal pressure capacity is reduced with increased axial compressive load, but the failure mode is different for high internal pressure and modest internal pressure. The results are compared with the laboratory tests in the project assessment report.

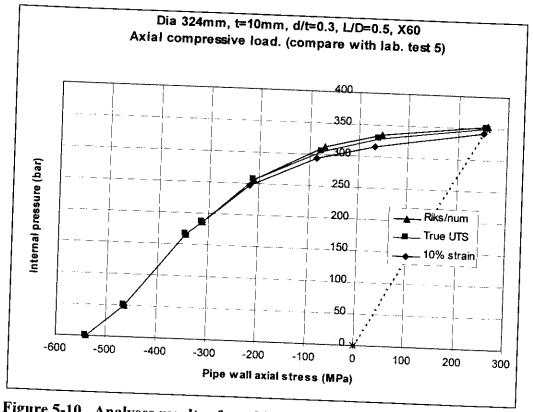


Figure 5-10 Analyses results of combined internal pressure and axial loads



6 CIRCUMFERENTIAL CORROSION DEFECTS, COMBINED LOADS

6.1 Models description

The analyses with circumferential corrosion defects were axis-symmetric models, using 8-noded axis-symmetric 2D elements. Only 2 models were used, and different load sequences were applied to the models, resulting in approximately 15 analyses. The pipe diameter was 324mm, wall thickness 10.4mm, and the actual material properties of the pipe were used. The corrosion defect was in the full circumferential with a longitudinal extent of 12 mm and a depth of 50% and 70% of the wall thickness. The model with 50% corrosion depth is shown in figure #. The model utilise the symmetry of both the load and the geometry, and for an illustration the model with 50% corrosion depth and 70% corrosion depth are mirrored twice in figure # and #. Note that only ¼ of the shown illustrations are the actual model.

6.2 Loading and failure criteria

Several analyses with various load paths of internal pressure and axial load were performed with the two models. First the internal pressure were applied to a defined level, and while keeping the internal pressure constant an axial compressive force was applied until failure. If only internal pressure was applied the models failed in the hoop direction as observed for the models with longitudinal corrosion. The burst failure was not observed in the analyses when the internal pressure was at a modest level. When applying axial compressive force this resulted in excessive plastic deformations, without indications on the pipe would have bursted. When large deformations were observed, approximately 10% strain, the analysis had reached the failure.

6.3 Results

The analyses results are included in figure # for both the 50% and the 70% corrosion depth models. For internal pressure only and not including the end cap force, the predicted capacity is almost identical for the 50% and the 70% corrosion depths. This illustrates that the load carrying capacity is in the hoop direction and that the pressure load in the corrosion defect is carried by the adjacent material. For a thin wall pressure container the axial stress is half the hoop stress (internal pressure loading only). In case of a full circumferential corrosion defect of 50% of the wall thickness, the axial stress in the corroded cross section has to carry the same load and hence the axial stress is increased to twice compared to the uncorroded section. In this case the axial stress in the corroded section is equal to the hoop stress in the uncorroded pipe. In this case it is expected that the capacity for a rupture due to the axial stress is close to the same as for a rupture due to the hoop stress. In case of 70% corrosion depth the axial stress in the corroded section exceeds the hoop stress in the uncorroded pipe by a factor of 1.66. It is therefore expected that the hoop stress, see the drop in the capacity curve for the 70% corrosion defect for tensile axial stress.



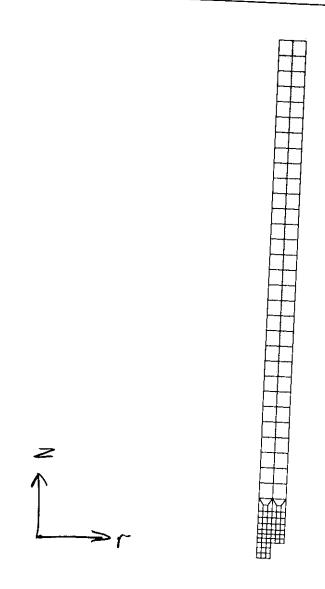


Figure 6-11 FE model of circumferential corrosion, 50% corrosion defect.

Accordingly, for compressive axial stress, the axial capacity will be exceeded before the hoop stress capacity for modest internal pressure and large axial compressive forces. Different from tensile stresses, the compressive stresses will only result in excessive deformations and no rupture. However, the large deformations also results in rotations and local bending of the pipe wall which also results in tensile stresses which could induce rupture.

The failure criterion is 10% strain in the corroded section. Two examples of exceeding the 10% criterion is indicated, where the one for 50% corrosion depth and 300 bar were analysed all to 70% strain.



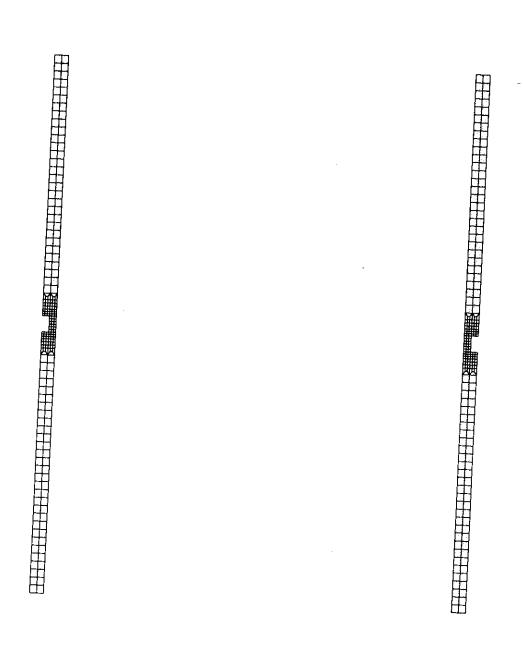


Figure 6-12 Illustrative view of the model with 50% corrosion depth. Only $\frac{1}{4}$ of the shown elements are used in the finite element analyses, see previous figure.



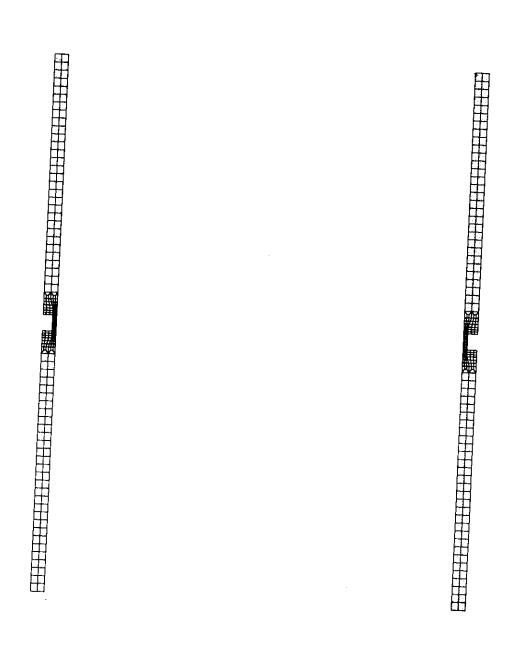


Figure 6-13 Illustrative view of the model with 70% corrosion depth. Only $\frac{1}{2}$ of the shown elements are used in the finite element analyses.



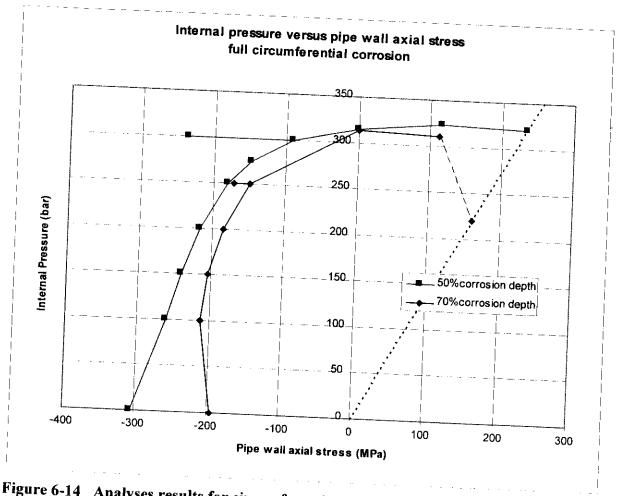


Figure 6-14 Analyses results for circumferential corrosion defects.

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REFERENCES

7 REFERENCES

ABAQUS v 5-4 (1995), Hibbitt, Karlsson and Sorensen, Providence, Rhode Island, USA Fu ,B. and Kirkwood, M. G. (1995), "Predicting Failure Pressure of Internally Corroded Linepipe using the Finite Element Method", Offshore Mechanics and Arctic Engineering, OMAE'95, Copenhagen

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