Strength and Deformation Capacity of Corroded Pipes

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SUMMARY. In the last ten years, a lot of efforts have been dedicated to estimate the remaining strength of corroded pipelines subject to internal pressure (bursting-pressure containment failure mode). Considering the future development for offshore pipelines, moving towards difficult operating condition (longer tie-back pipeline under internal corrosive conditions, sometime sweet more frequently sour) and deep/ultra deep water applications (where the corroded pipelines might be subject to shut-down and shut-in conditions during their operative lifetime) there is the need to understand the failure mechanisms and better quantify the strength and deformation capacity of corroded pipelines considering the relevant failure modes (bursting, collapse, local buckling, fracture/plastic collapse etc.), which can be activated during installation and operation.
Several studies and experimental test programs have been carried out aiming to quantify the strength and deformation capacity of corroded pipes subject to differential pressure, axial force and bending moment.
In this paper, the following is discussed:

- The failure mechanisms of corroded pipes, relevant design criteria available in the standards are briefly described;
- The ABAQUS FE Model, developed to quantify the strength and deformation capacity of the pipe subjected to internal pressure, external pressure, steel axial force and bending moment;
- The validation/calibration of the FE analysis outcomes with experimental tests results available in the relevant literature;
- A FE Model parametric study has been carried out to quantify the strength and deformation capacity of corroded pipes under combined load conditions;
- The limitations of the developed FEM are discussed and recommendations are given for further studies to better quantify the limit loads and deformations of corroded pipes under combined load conditions.

1 FAILURE MECHANISMS

The failure mechanisms of pipes with corrosion defect subject to combined load condition i.e. internal pressure, axial force and bending moment, depend on several parameters i.e. steel pipe diameter (D), pipe diameter to thickness ratio (D/t), pipe segment length to diameter ratio (l/D), stress-strain relationship (yield stress, ultimate stress and uniform elongation), steel axial force (N, generally normalized with the yield axial force, N_y), internal pressure (p_i, generally normalized with the yield internal pressure, p_y), pipe initial ovalisation (O_v), pipe initial curvature, girth weld characteristics (residual stresses, pipe misalignment at the joint, change in material properties in the heat affected zone, HAZ, and pinching deformations that arise at the weld from the thermal contractions and contribute to the initial pipe deformations), corrosion defect location with respect to the loads, corrosion pattern (simple, multiple and interacting metal losses) and metal loss dimensions i.e. corrosion depth to pipe thickness ratio (d/t), corrosion length to pipe diameter ratio (L/D) and corrosion width to pipe diameter ratio (c/D), see for example Refs. /1/ and /2/.

Figure 1-1a to Figure 1-1c shows the typical failure mechanisms/modes of intact and corroded pipes subject to internal pressure. An outward bulge failure mechanism develops for the intact pipe, see Figure 1-1a. By contrast, for the corroded pipes, the localised bulge and tear developed in the region where failure occurs is less visible than for the intact pipe, mainly because of the lower strain energy level stored in this tube before failure, see Figure 1-1b and Figure 1-1c.

The failure modes for intact and corroded pipes under external pressure are shown from Figure 1-2a to Figure 1-2e. The corrosion patterns on the pipe surface (width, depth and location of the corrosion defect) affect the collapse behavior and the deformation shape during and after failure.

In case of combined load condition i.e. internal/external pressure, steel axial force and bending oment, the failure mechanism is generally named local buckling mechanism. The local buckling mechanism under progressive bending is genearrly classified as follows:

- *Diamond buckling mode*
  The pipe exhibits, at the sector in compression, a series of ripples resembling the facets of a diamond, at elastic strains. As the pipe continues to bend, a kink develops (D/t greater than 100, limit strains affected by concomitant axial load and, weakly, internal pressure).
- *Wrinkling buckling mode*
  The pipe exhibits, at the sector in compression, a series of wrinkles, perpendicular to pipe axis, at strains exceeding yielding. As the pipe continues to bend, localization causes one outward bulging, with two small depressions adjacent to it (D/t 60 to 100, limit strains affected by concomitant axial load and internal pressure).
- *Outward bulge buckling mode*
  The pipe exhibits, at the sector in compression, a series of wrinkles, perpendicular to pipe axis, at strains exceeding yielding. As the pipe continues to bend, the inelastic deformation localizes in one central wrinkle, which develops outwards up to causing circumferential tearing at the crest (D/t < 60, limit strains affected by internal pressure).

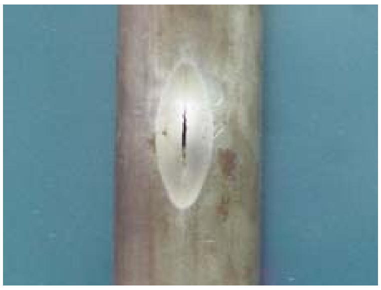
For a corroded pipe subject to combined loads, the failure / buckling mechanism is influenced by the presence of internal pressure and location of the metal loss across the pipe circumference. In particular the following considerations apply:

- *Metal loss in the tensile fiber*
  For the no inner pressure cases, the pipe undergoes an ovalisation buckle, see Figure 1-3a. While in the cases analysed with internal pressure, yielding occurs in the zone where the thickness is reduced due to metal loss and the maximum bending moment is reached when the corroded area does not have any capacity to sustain additional local loads.
- *Metal loss in the compressive fiber*
  If the corroded area is in the compressive fiber the maximum bending moment is reached as the pipe buckles developing a wrinkle that has a limited extension in the longitudinal direction (see Figure 1-3c), depending on the corroded area axial length. The presence of the inner pressure makes the buckle to grow up more rapidly than the cases without pressure and it also increases the buckle length (compare Figure 1-3c and Figure 1-3d). However the wrinkle

axial extension in the axial direction is reduced with respect to the correspondent case without metal loss.

a) Intact pipe

b) Corroded Pipes



c) Corroded Pipes

Figure 1-1 – Typical failure mechanisms of intact and corroded pipes subject to internal pressure.

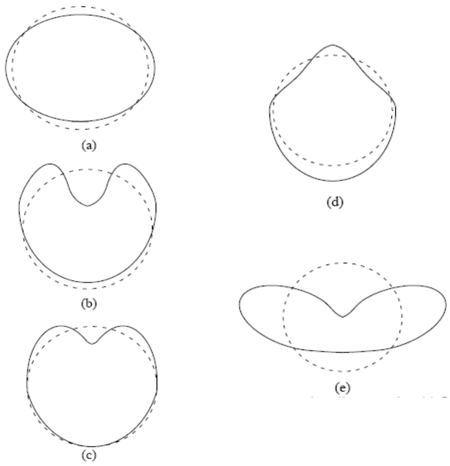
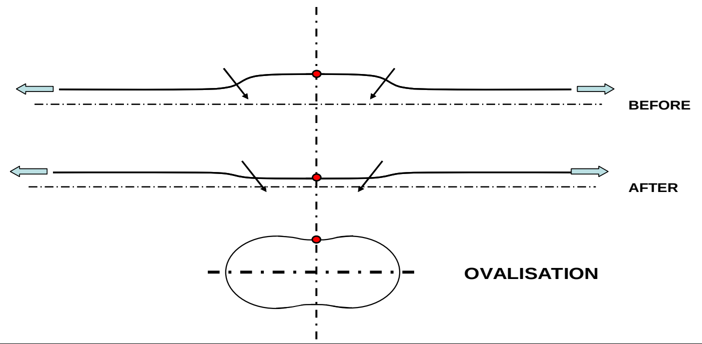
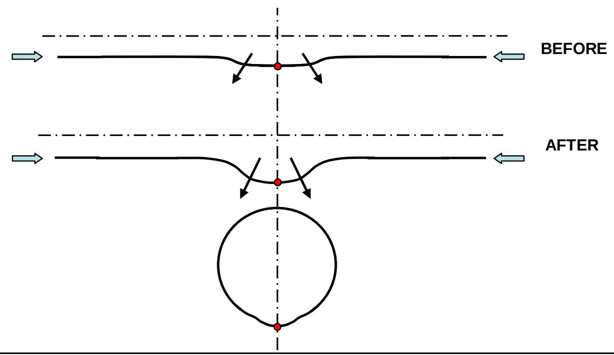


Figure 1-2 – Typical failure mechanisms of intact and corroded pipes subject to external pressure. Symmetrical Collapse Modes: (a) Flat Mode; (b) U1-Mode; (c) U2-mode; (d) "Pear"-mode; (e) U3-mode.



a) Pipe model after bending showing the buckle zone: (corroded area in **tension**).



Pipe model after bending showing the buckle zone: (corroded area **in compression**).

Figure 1-3 – Buckling mechanisms of pipes subject combined loads.

Offshore Pipeline Standards gives some recommendations and criteria for assessing the strength and deformation capacity of corroded pipes, see for example, DNV Standards, ASME B31G, BS 7910, API RP 579 and ABS (Refs. /3-/9/).

Analytical studies are available for the the different load conditions, see for example Refs. /10/-/12/ and /13/-/14/.

Several experimental tests were carried out with the aim to better identify the deformation/failure mechanisms on corroded pipes subject to the only internal pressure. On the contrary, a few experimental tests were carried out applying only the external pressure or combined loads i.e. pressure, axial load and bending moment, see for example, the work by British Gas (Refs. /15/ and /16/), Ocean Engineering Department (Ref. /17/-/18/), Korea Gas Company (Ref. /19/), Petrobras & University of Rio de Janeiro (Refs. /20/-/21/) and Southwest research Institute, SWRI (Refs. /22/-/23/).

At the moment, standard FEM-based structural computer programs give robust and reliable results when compared with experimental test results in terms of failure shape and loads. Generally, ABAQUS software is used more extensively, however, other computer programs available on the market can be used provided that large displacement, large rotation and finite strain deformation theory are available, see for example, the work performed by British Gas (Ref. /24/), Ocean Engineering Department (2001, internal pressure, see Ref. /17/-/18/), Petrobras & University of Rio de Janeiro (Refs. /25/ and /27/), Korea Gas Company (Ref. /19/), Zhejiang

University of China (Ref. /28/), SERCON Consulting Services (Ref. /26/) and Southwest Research Institute, SWRI (Refs. /22/-/23/).

2 ABAQUS FE MODELS

2.1 *General Description*

ABAQUS FEM-Based structural computer code (Refs. /29/-/30/) have been used to develop the FE Models with the aim to predict the failure mechanisms, the limit loads and the limit deformation of corroded pipes under combined loads (Refs. /31/-/32).

Two main FE Models have been developed:

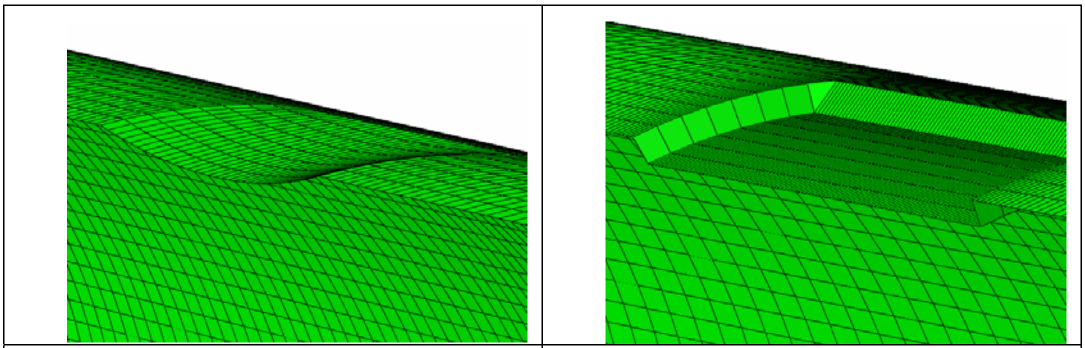
- *Shell Element - Based FE Model* with a constant number of elements in the hoop direction. Sensitivity analyses have been performed on the mesh size in the hoop and axial direction. The mesh size in the hoop direction and in the axial direction has been selected on the basis of the characteristics pipe dimensions (diameter, steel wall thickness etc.), corrosion dimensions (depth, length and width), loading conditions etc. S4R shell elements were used (Refs. /29/-/30).
- *Solid Element - Based FE Model* with a constant number of elements in the hoop direction. Sensitivity analyses have been performed on the mesh size in the hoop and axial direction and element type. The mesh size in the hoop, axial and radial direction has been selected on the basis of the characteristics pipe dimensions (diameter, steel wall thickness etc.), corrosion dimensions (depth, length and width), loading conditions etc. C3D8R solid elements were used (Refs. /29/-/30).

The material discontinuity has been modelled considering both parabolic (in the longitudinal and hoop direction) and uniform thickness variation (with a linear transition on one element), see Figure 2-4. Different mesh sizes in the longitudinal and hoop direction are used, see Table 2-1. The mesh size is refined in correspondence of the defect region.

The non-linear material behaviour is opportunely considered using the true stress-strain curve and the von-Mises associated plastic flow (Refs. /29/-/30/).

For the difeerent load conditions, the following loading sequence has been considered:

- *Internal or external overpressure*
    1. The internal or external pressureis increased up to reaching the maximum internal / external pressure.
- *Combined loads with external overpressure*
    2. External pressurization up to about 70% of the collapse pressure of the intact pipe (= 9 MPa in the pilot study). A compressive axial load has been applied on the pipe model to take into account the action of external pressure on the closed specimen ends.
    3. Pipe bending up to the maximum or limit bending moment.
- *Combined loads with internal overpressure*
    1. Internal pressurization up to about 40% of the bursting pressure of the intact pipe (=15 MPa in the pilot study). A tensile axial load has been applied on the pipe model to take into account the action of internal pressure on the closed specimen ends.
    2. Pipe bending up to the maximum or limit bending moment.



a)	b)

Figure 2-4 – Parabolic (a) and Uniform (b) Corrosion Defect Depth.

ID	HOOP NODES	LONG. NODES	ELEMENT LENGTH IN THE LONGITUDINAL DIRECTION	ELEMENT LENGTH IN THE HOOP DIRECTION	ELEMENT LENGTH IN THE RADIAL DIRECTION (for solid elements)
Lt2Ht1	25	213	Thickness / 2	Thickness	Thickness / 5
Lt2Ht3	71	213	Thickness / 2	Thickness / 3	Thickness / 5
Lt6Ht1	25	277	Thickness / 6	Thickness	Thickness / 5
Lt6Ht3	71	277	Thickness / 6	Thickness / 3	Thickness / 5

Table 2-1 – Mesh Sizes in correspondence of the Defect.

2.2 *FEM Validation*

The FEM Model results have been compared with experimental tests results. The experimental tests related to the collapse capacity of corroded pipes by Netto have been used, considering the following pipes (Ref. /17/):

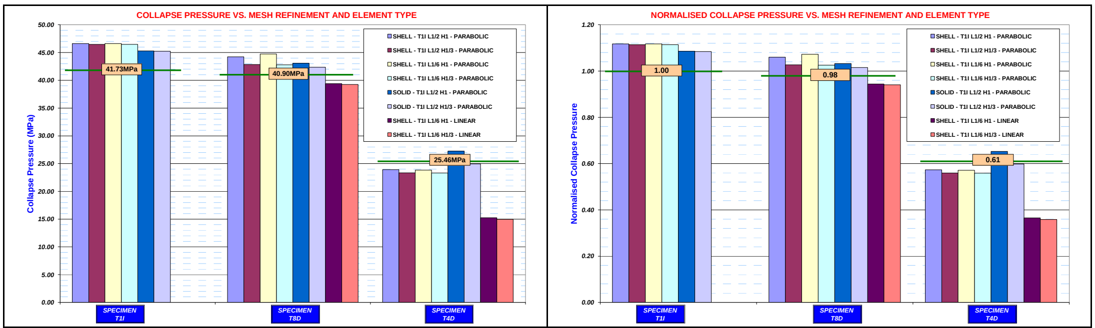
- Intact pipe (T1I test number in Ref. /17/),
- Defected pipes with a metal loss through the thickness equal to 20% (T8D test number in Ref. /17/),
- Defected pipes with a metal loss through the thickness equal to 70% (T4D test number in Ref. /17/), respectively.

Both shell and solid elements have been considered in the FE analyses and the relevant parameters along the pipe have been monitored at the collapse. The collapse pressure is strongly affected from the defect shape and dimension. In case of shell elements, both parabolic and uniform wall thickness variations have been investigated, see Table 2-2 and Figure 2-5a and Figure 2-5b. The experimental results are reported and the relative values are normalised with respect to the experimental collapse pressure of the intact pipe (=41.73 MPa).

The FEM analyses carried out using shell and solid elements provide comparable results and a good accuracy with respect to the experimental results, see Table 2-2.

Test	Minimum Deviation from Experimental Results	
	Shell	Solid
T1I	+11%	+8%
T8D	+5%	+4%
T4D	+4%	-1%

Table 2-2 – FEM Validation - Minimum Deviation of FEM results from Experimental Values.



a) Collapse Pressure of Each Specimen using Different FE Models

b) Normalised Collapse Pressure of Each Specimen using Different FE Models

Figure 2-5 – FEM Validation - Collapse Pressure Comparison i.e. FEM vs. Test Results.

3 PILOT STUDY

3.1 *Basic Data*

The relevant informations about pipe dimensions and defect geometry are listed in Table 3-1.

The nominal steel grade of pipe is X65. The engineering stress-strain curve of the pipes used in the FE analyses is shown in Figure 3-7. The average Young's modulus (E), Poisson's ratio (ν), and 0.2% yield stresses (σ_0) are equal to:

- Modulus of elasticity 207 000 MPa
- Yield Stress (SMYS) 450 MPa
- Ultimate Stress (SMTS) 535 MPa
- Poisson's Ratio 0.3

Both shell and solid elements have been used to model the intact and corroded pipes as described in Table 3-1. The corroded area has been modelled considering a parabolic thickness variation in the longitudinal and hoop direction, see Figure 2-4.

The mesh size is refined in correspondence of the defect region. After this region, the longitudinal elements dimension increases gradually to reduce the size of the FE Model.

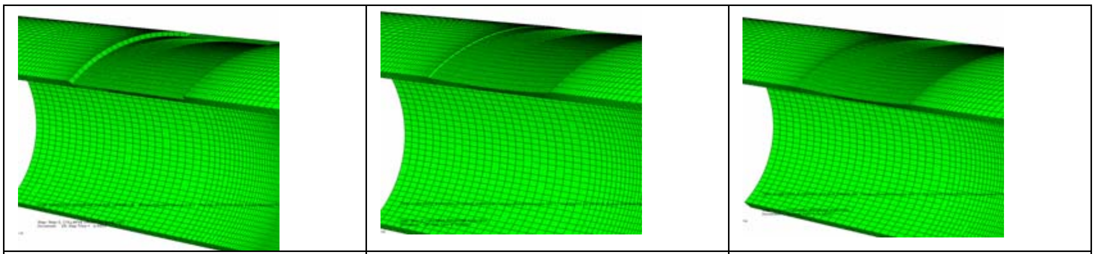
The defect is positioned so that the minimum thickness was coincident with the minimum diameter of the ovalised cross-section.

A sensitivity FEM analysis has been performed aiming to evaluate the corrosion shape influence on the limit bending moment reduction of corroded pipe subjected to combined loads of internal pressure, axial compression and increasing bending moment. The following corrosion shapes have been considered:

- Uniform corrosion depth (Figure 3-6a),
- Sharp parabolic corrosion depth (Figure 3-6b),
- Smooth parabolic corrosion depth (Figure 3-6c).

Test	D (m)	t (mm)	D/t	L_R (d/t)	L_A (l/D)	L_H (c/D)	Ovality	Material	Location	Tests
Intact Pipe	0.61	20.3	30.0	--	--	--	1%	X65	--	ALL
Corroded Pipe 1	0.61	20.3	30.0	0.3	0.5	0.5	1%	X65	Compression vs. Tension & Internal vs. External	Collapse Pressure & Combined Loads (P_{ext})
Corroded Pipe 2	0.61	20.3	30.0	0.5	1.0	1.0	1%	X65	Internal vs. External	Combined Loads (P_{int})

Table 3-1 – Pilot Study – Pipe Data.



a) b) c)

Figure 3-6 – Pilot Study - Corrosion Defect Shapes considered in the FEM Analyses of Pipe subjected to Combined Loads with Internal Pressure.

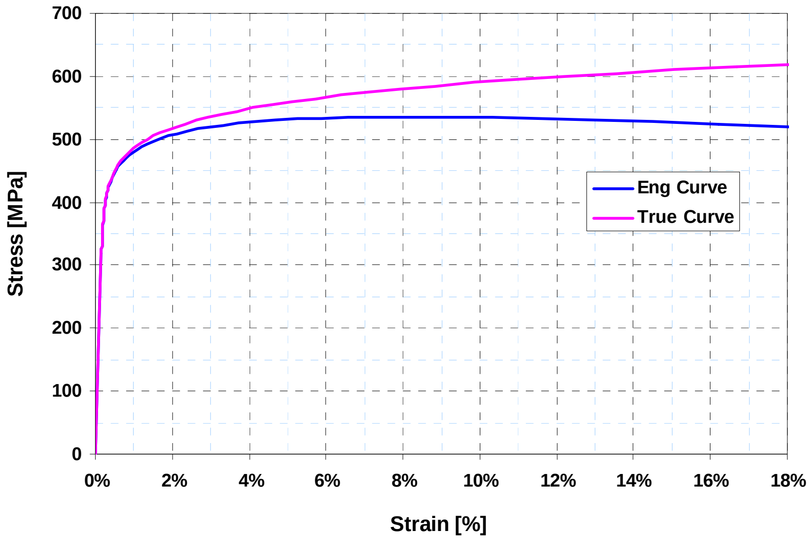


Figure 3-7 – Stress-Strain Material Curve for X65 Steel Grade.

3.2 *Combined Load Condition – Bending Moment in presence of External Overpressure*

FE analyses have been carried out to quantify the limit bending moment of corroded pipes subjected to combined loads of external pressure, axial compression and increasing bending moment. The detailed pipe data used in the FE analyses are described in Table 3-1.

FE results using solid and shell elements have been compared and the relevant parameters along the pipe have been monitored up to the maximum bending moment at the mid-span pipe section (Table 3-2).

The failure mode is significantly affected from the corrosion defect location on the pipe surface. In particular, the corrosion defects have been located in the following locations:

- Internal pipe surface – H=0 (compressive fibers),
- Internal pipe surface – H=6 (tensile fibers),
- External pipe surface – H=0 (compressive fibers),
- External pipe surface – H=6 (tensile fibers),
- Internal pipe surface – Double Defect (tensile and compressive fibers),
- External pipe surface – Double Defect (tensile and compressive fibers).

Figure 3-9 shows an example of the deformed pipe configurations at the maximum bending moment obtained with shell and solid FEM.

From the FEM analysis carried out the following conclusions can be deduced:

- The FEM analyses carried out using shell and solid elements provide comparable results (Figure 3-8a to Figure 3-8e).
- The presence of a defect along the pipe surface influences the collapse failure mode of the pipe. The external pressure causes a local pipe ovalisation along the corroded area and during bending and compressive axial load the local pipe deformation increases up to the rupture, see Ref. /17/.
- A smooth parabolic corrosion defect gives a negligible limit bending moment reduction if located along the internal pipe surface (Table 3-2) or along the tensile fibers. A slight strength

capacity reduction with an increased local deformation is evidenced considering external corrosion defects in the compressive fibers where the pipe ovalisation buckling mode appears.

- Stresses and deformations localise in the defect region as the external pressure increases. When the corrosion defect is located along the compressive fibers, the minimum longitudinal strain at the limit bending moment increases passing from -0.45% to -2.74% for the intact and externally corroded pipe, respectively (Figure 3-8d). At the contrary, if the corrosion defect is located along the tensile fibers, the maximum longitudinal strain at the limit bending moment increases passing from -0.42% to -1.27% for the intact and internally corroded pipe, respectively (Figure 3-8c).
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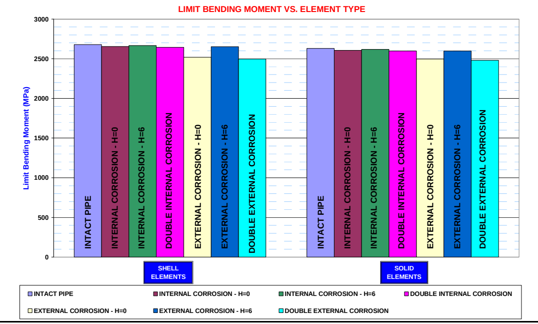
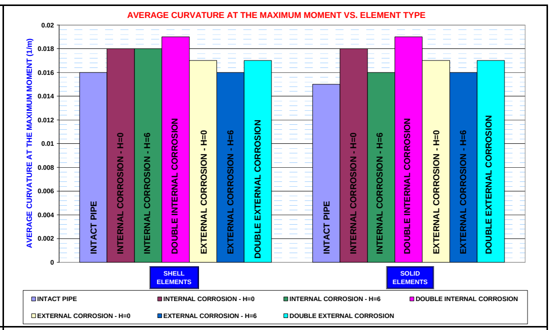
Test	Corrosion	Limit Bending Moment (kNm)	Ave. Curvature at the Max. Moment (1/m)	Maximum Local Longitudinal Strain at the Max. Moment (%)	Minimum Local Longitudinal Strain at the Max. Moment (%)	Sectional Pipe Ovalisation at the Max. Moment (%)	Min. Local Hoop Strain at the Max. Moment (%)
SHELL	Intact	2679	0.016	0.46	-0.49	6.05	-0.64
	Internal h=0	2653	0.018	0.41	-1.69	6.00	-0.57
	Internal h=6	2666	0.018	1.43	-0.48	5.78	-1.29
	Double Internal	2643	0.019	1.26	-1.64	5.73	-1.14
	External h=0	2518	0.017	0.31	-2.90	6.07	-1.36
	External h=6	2651	0.016	1.22	-0.46	5.27	-1.12
	Double External	2497	0.017	0.84	-2.60	5.87	-1.20
SOLID	Intact	2629	0.015	0.42	-0.45	6.16	-0.54
	Internal h=0	2605	0.018	0.41	-1.57	7.34	-0.56
	Internal h=6	2617	0.016	1.27	-0.43	5.85	-1.13
	Double Internal	2598	0.019	1.15	-1.51	6.87	-1.08
	External h=0	2497	0.017	0.31	-2.74	6.88	-1.24
	External h=6	2597	0.016	1.18	-0.44	6.56	-1.10
	Double External	2480	0.017	0.80	-2.69	7.02	-1.22

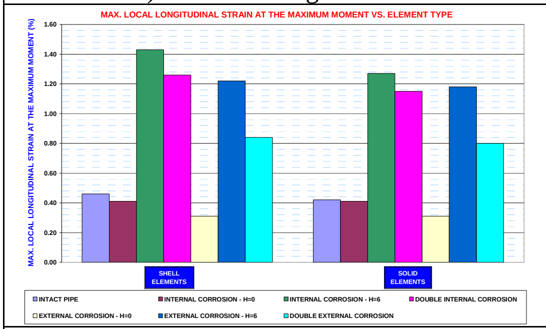
Table 3-2 – Pilot Study - Combined Loads with External Pressure - FE Analyses Results using Shell and Solid Elements.



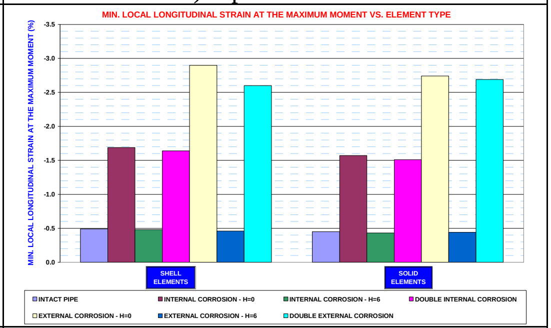
a) Limit Bending Moment



b) Pipe Curvature

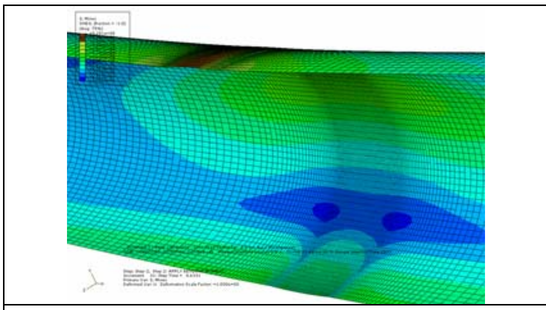


c) Maximum tensile strain

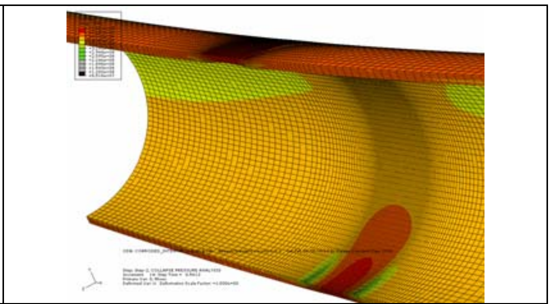


d) Minimum axial strain

Figure 3-8 – Pilot Study – Combined load condition with external overpressure for the Intact and Corroded Pipe using Shell and Solid Elements.



a) Shell Element Analysis



b) Solid Element Analysis

Figure 3-9 – Pilot Study – Combined load condition with external overpressure - Deformed Pipe Configurations at the Limit Bending Moment with the Double Corrosion Defect Located on the Internal Pipe Surface.

3.3 *Combined Load Condition – Bending Moment In presence of Internal Overpressure*

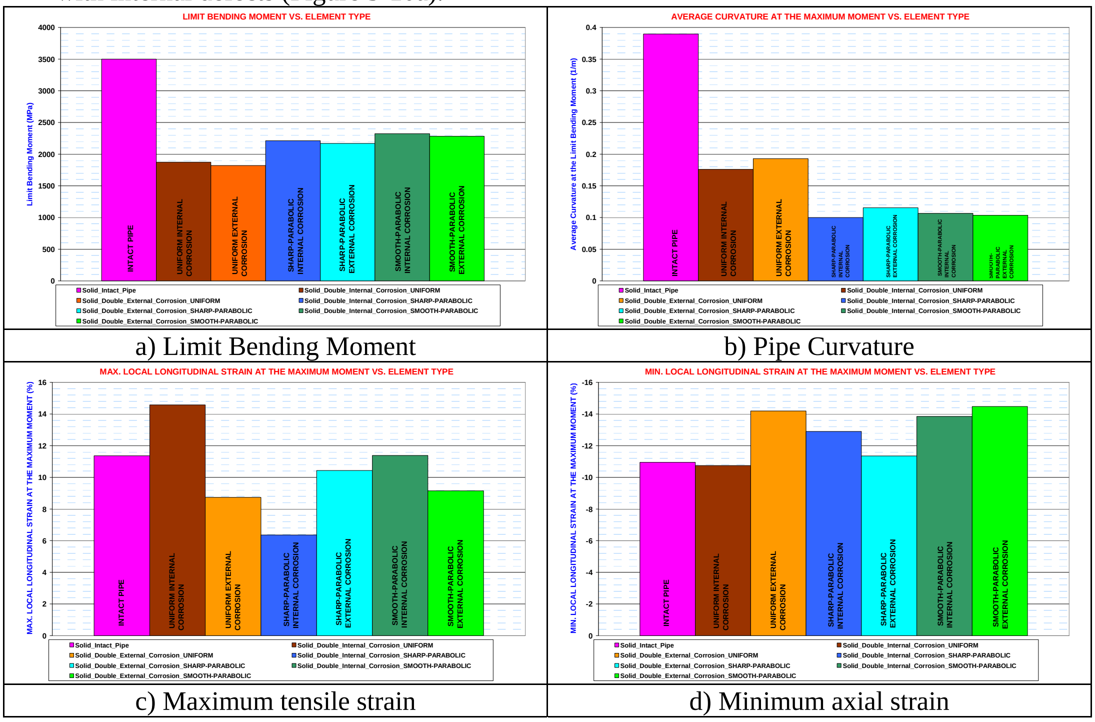
FE analyses have been carried out to quantify the limit bending moment of corroded pipes subjected to combined loads of internal pressure, axial tension and increasing bending moment. The detailed pipe data are described in Table 3-1. A double corrosion defect (along the tensile and compressive fibers) has been considered in the FE analyses.

A solid element based FE model has been considered to perform FEM analyses, as decribed in Section 2 and the relevant parameters along the pipe have been monitored up to the maximum bending moment at the mid-span pipe section (Table 3-3).

A sensitivity FEM analysis has been performed aiming to evaluate the corrosion shape influence on the limit bending moment reduction of corroded pipe. Figure 3-6 shows the corrosion defect shapes considered in the FEM analyses.

From the FEM analysis carried out the following conclusions can be deduced:

- The presence of a defect along the pipe surface influences the collapse failure mode of the pipe. The Internal pressure causes a local wrinkle along the corroded area and during bending and compressive axial load the local pipe deformation increases in the compressive fibers up to the rupture.
- Corroded pipes show a strength capacity reduction function of the corrosion defect shape. A smooth parabolic corrosion defect causes a lower strength reduction during bending (36% from the intact pipe) while considering a uniform corrosion depth a remarkably limit bending moment reduction is evidenced (50% from the intact pipe), Figure 3-10a.
- External corrosion defects show a pipe strength capacity reduction slight higher than the ones with internal defects (Figure 3-10a).



a) Limit Bending Moment | b) Pipe Curvature | c) Maximum tensile strain | d) Minimum axial strain

Figure 3-10 – Pilot Study – Combined load condition with internal overpressure for the Intact and Corroded Pipe using Shell and Solid Elements.

Test	Corrosion	Limit Bending Moment (kNm)	Ave. Curvature at the Max. Moment (1/m)	Maximum Local Longitudinal Strain at the Max. Moment (%)	Minimum Local Longitudinal Strain at the Max. Moment (%)	Sectional Pipe Ovalisation at the Max. Moment (%)	Max. Local Hoop Strain at the Max. Moment (%)
SOLID	Intact	3661.0	0.390	11.36	-10.95	16.51	9.15
	Internal - UNIFORM	1875.0	0.176	14.58	-10.75	3.23	11.41
	External - UNIFORM	1821.0	0.193	8.73	-14.20	2.35	11.80
	Internal – SHARP P.	2213.6	0.100	6.36	-12.90	2.80	12.42
	Double – SHARP P.	2169.7	0.115	10.43	-11.35	3.90	13.54
	Internal – SMOOTH P.	2324.3	0.107	11.39	-13.85	2.96	13.16
	External - SMOOTH P.	2281.9	0.104	9.15	-14.48	3.77	12.60

Table 3-3 – Pilot Study - Combined Loads with Internal Pressure - Solid Elements.

4 CONCLUSIONS

The review of the available literature on the strength and deformation capacity of corroded offshore and onshore pipelines, evidence as follows:

- In the standards and codes, design criteria and equations are generally suitable for the verification of the pressure containment capacity of corroded pipes under internal pressure dominted load condition.
- Numerical studies and experimental tests have been performed in the last 15 years aiming to investigate the failure mechanisms and quantify design criteria and equations for the offshore pipelines subject to external / inernal pressure combined with steel axial force and bending moment.
- FE Models, calaibrated using experimental tests, have been developed and used as a numerical laboratory to analyse the failure mechanisms and limit loads of offshore pipelines with single corrosion and interacting defects.

The comparison of the FE Models, developed in this work and suitable calibrated with experimental tests available considering external pressure dominated load conditions, shows as follows:

- Shell and solid element-based FE Models give comparable results with respect to experimental ones (1%÷5% discrepancy with respect to test results).
- Solid elements permit a greater flexibility in the corrosion defect modelling. FE analyses using brick elements require a CPU calculation time 2-3 times greater than the ones performed using shell elements.

Experimental tests are needed to validate FEM results for combined load conditions under internal pressure combined with steel axial force and bending moment.

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