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COLLAPSE PRESSURE OF REELED RIGID PIPES

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Abstract. This work deals with a numerical and experimental investigation on the effect of plastic strains inferred to steel pipes during reeling installation process and its subsequent effect on the collapse pressure of these pipes. Experimental tests on full-scale models were carried out in order to calibrate a numerical tool to simulate the whole process. Pipe samples are bent and straightened over the rigid surfaces of circular dies. Subsequently, the samples are tested quasi-statically under external pressure until collapse in a pressure vessel. A three-dimensional nonlinear finite element model was developed to simulate the bending and straightening process as it occurs during installation. The model was implemented with the dimensions and initial imperfection measured on test samples and takes into account finite displacements and elastic-plastic behavior under the Mises potential flow law with isotropic or kinematic hardening. The model is then used to determine the collapse pressures of plastically strained pipes and evaluate the combined effect of the parameters that most affect its values.

1 INTRODUCTION

The installation process is a subject of concern for submarine pipelines design. The most efficient and cost-effective method involves pipe onshore welding and pipeline bending over a rigid circular surface (reel) positioned on the deck of an installation vessel. During offshore installation at deep sea, the pipeline is straightened and launched under tension.

Therefore, the loading cycles of bending and straightening during the installation phase introduces stories of loading with deformations within the elastic-plastic regime of the material. Although the pipe is straightened prior to launch, distortions in the form of residual out-of-roundness, residual stresses, changes in material properties due to plasticity, and growing of eventual welding flaws may occur. These effects may have an influence on both ultimate strength and subsequent fatigue performance of the pipeline.

During installation or under operation, subsea steel pipes will be subjected to different mechanical loads, such as twisting, axial tension, longitudinal bending and radial pressure. The loads may be of constant amplitude or oscillating in time for the dynamic systems (i.e., risers). For deepwater pipelines, external pressure is the critical design load (Yeh and Kyriakides, 1986). The factors governing the collapse of steel pipes under external pressure have been extensively studied so that nowadays, deepwater pipes can be safely designed (Murphey and Langner, 1985, Netto and Estefen, 1994). On the other hand, the plastic strains inferred to a pipe during the reeling installation process and its effect on the collapse pressure can be better understood.

The collapse pressure of single wall steel pipes is mainly dependent on tree parameters: diameter to thickness ratio, out-of-roundness and yield stress. The wall thickness eccentricity and the residual hoop stress may also affect the collapse pressure (Yeh and Kyriakides, 1986) but its effects are of second order. It is interesting to note that reeled pipes have both its out-of-roundness (ovalization) and yield stress increased due to the plastic deformations inferred, at least for work hardening materials. A larger ovalization will decrease the collapse pressure while a higher yield stress will increase. Here, It will be shown how much these parameters can affect the collapse pressure of the analyzed large-scale models under different material properties (axial or hoop) and types of strain hardening modeling (isotropic or kinematic).

This paper also describes the experimental facility designed by Subsea Technology Laboratory – COPPE/UFRJ to reproduce the reeling/straightening process of full-scale pipes. The facility was used to perform a series of experiments on 8.625" OD pipes (Pasqualino et al., 2004). Initially, the external surfaces of the samples were mapped to determine geometric parameters before and after reeling/straightening. After being reeled and unreeled, the pipes models were sealed and collapsed in a 10.000 psi hyperbaric chamber. The experimental collapse test also included intact samples of the same geometry of the reeled pipes.

In this study, the experimental results were used to calibrate a three-dimensional nonlinear finite element (FE) model that is capable to simulate the reeling process and the collapse under external pressure. The FE model was adjusted through different constitutive theories to reproduce the physical experiments. From the obtain results some conclusions about the main parameters governing the collapse pressure of reeled pipes will be presented.

2 SAMPLES PROPERTIES

Eight samples were prepared: five of them to be reeled, straightened and collapsed and others three to be collapsed only. The sample nominal material and geometric parameters are:

- Material: API5L X60;
- Outside diameter: 219.08 mm;
- Thickness: 15.06 mm;
- Length: 2.0 (collapse only) or 5.2 m.

For the collapse only experiments, the samples were prepared with an approximate length of ten times its external diameter (≈ 2m). The five others to be first bent were made with 5.2m length. In this case, after the bending/straightening tests, the pipes ends were cut out to meet collapse only test length. The nomenclature used to identify the test samples was so to show the original tube name (T1 to T3). The characters A, B, C and D distinguish samples coming from the same pipe.

Before each experiment, geometric parameters of the samples were measured and recorded. The measurement procedure and the obtained results are commented in details at Pasqualino et al. (2004). Table 1 reports the results of external diameter (D) wall thickness (t) initial ovalization (Δ_0) and wall thickness eccentricity (Ξ_o).

Sample	D (mm)	t (mm)	D/t	Δ_0 (%)	Ξ_o (%)
T1A	219.89	15.18	14.48	0.239	6.10
T1B	219.61	14.82	14.82	0.205	4.53
T2A	219.50	14.96	14.67	0.205	4.56
T2B	220.01	14.70	14.97	0.295	9.34
T3A	219.56	15.09	14.55	0.194	6.41
T3B	220.22	15.02	14.66	0.306	6.65
T3C	219.74	14.81	14.83	0.205	5.87
T3D	219.61	14.95	14.69	0.182	7.61
Average	219.77	14.94	14.71	0.229	6.38

Table 1: Geometric Parameters of the Pipe Samples

Pipe	Axial Direction				Hoop Direction			
	σ_o (MPa)	σ_u (MPa)	σ_o/σ_u	*E* (GPa)	σ_o (MPa)	σ_u (MPa)	σ_o/σ_u	*E* (GPa)
T1	424.8	442.3	0.96	206.4	498.0	667.1	0.75	191.6
T2	492.3	526.3	0.94	212.1	516.5	667.0	0.77	189.6
T3	483.7	491.3	0.98	217.6	501.3	653.0	0.77	188.7
Average	466.9	486.7	0.96	212.0	505.3	662.3	0.76	190.0

Table 2: Mechanical Properties of the Pipes

Finally, axial and hoop test coupons cut from each original pipe were tested under tension to measure their stress-strain response. Some pipes presented a monotonic work-hardening stress-strain curve in elastic-plastic range until failure (T2), while others had a Lüdder-band like type of instability (T1 and T3). The measured Young's modulus (*E*), 0.2% yield stress (σ_o) and tensile strength (σ_u) of each pipe are listed in Table 2. Though the nominal steel was X-60 (nominal yield stress equal to 60ksi), the actual yield stress (considering axial properties) varied from 424.75 to 492.33MPa (i.e., 61.6 to 71.4ksi), while the hoop yield stress varied from 498.00 to 516.32Mpa (i.e., 72.3 to 74.89ksi). It should be noted that the hoop test coupons were machined from a 3 mm thickness plane transverse section cut from each original pipe. Then, no initial strains were applied during the manufacturing process.

3 BENDING SIMULATOR

The bending simulator is in charge to induce plastic deformations on pipes through bending and reverse bending over rigid surfaces similarly to what occurs during installation procedures. It is composed of a main steel structure and dies with variable radii of curvature that are driven by two hydraulic actuators. The main characteristics of the facility are as follows:

- Maximum length of the samples: 5.4 m;
- Maximum external diameter of samples: 508 mm;
- Maximum driving force of the dies tools: 800kN;
- Radii of curvature of the bending dies: 6 and 8 m;
- Radii of curvature of the straightening dies: 30 and 40 m;

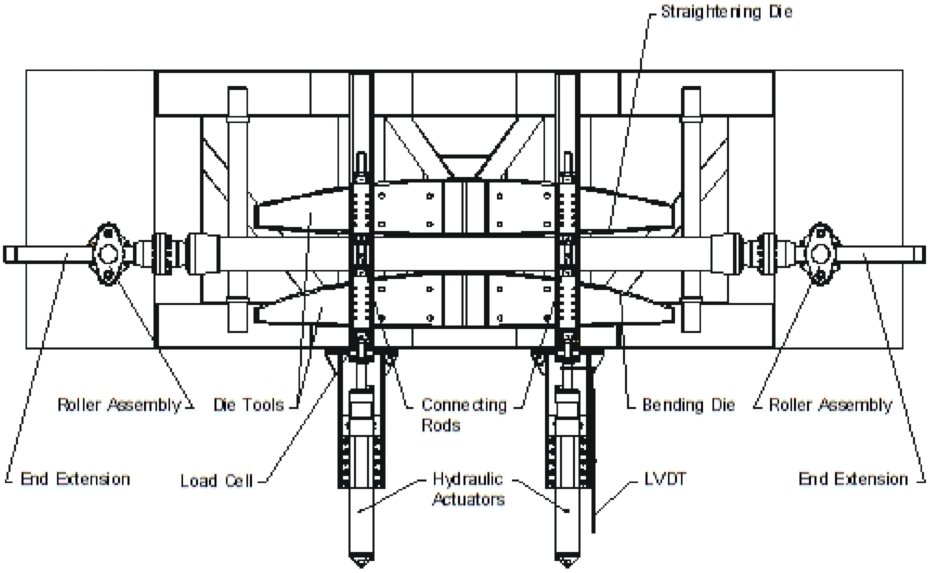
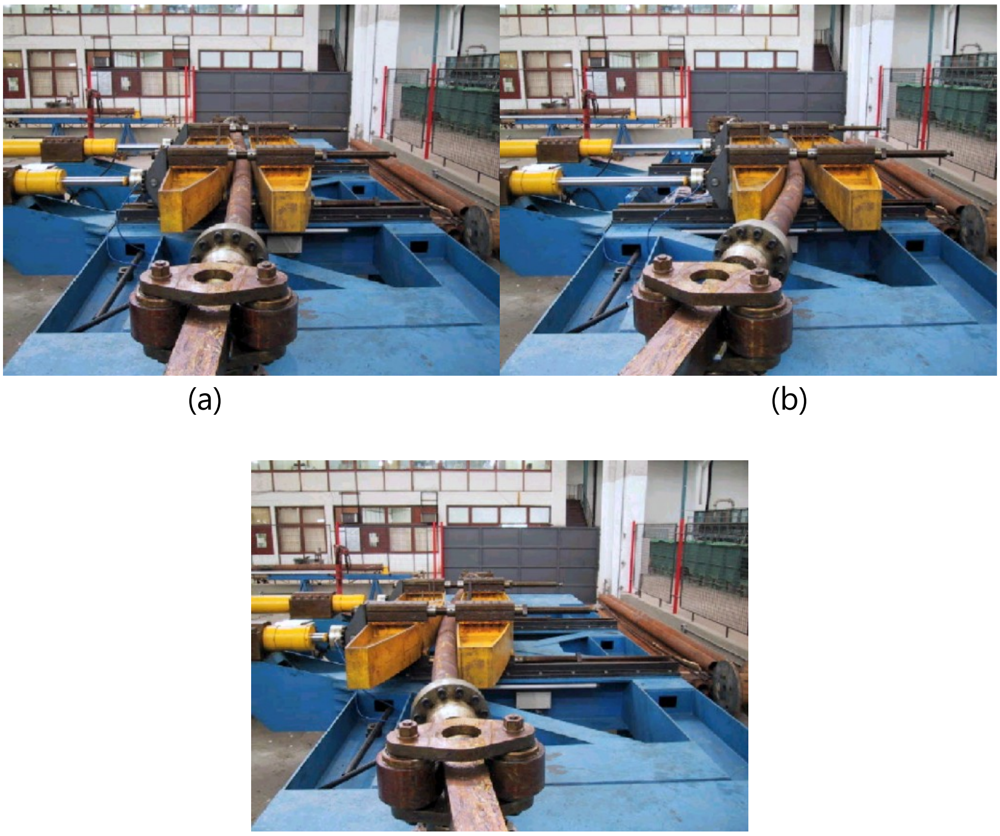


Figure 1: Top View of Bending Simulator

A simplified view of the bending simulator is shown in Figure 1. The pipe is placed between the bending and straightening dies, each of which being part of two different dies tools. The tools are connected to each other by two rods so as to form a single piece that embraces the sample. They are mounted on two leveled machined plates provided with one rail each where they can slide on back and forth. The plates are attached to an 8.5 m long, 2.7m wide and 0.8 m high self-supported steel structure. The pipe ends are attached to extension bars that react against one roller assembly on each side when the actuators apply force on the tools. The roller assemblies are designed to allow translation and rotation of the end extensions when the pipe samples are being bent and/or straightened. The sliding motion of the tools is driven by two hydraulic actuators supplied by a positive displacement pump, provided with a servo-valve in closed-loop control system. Two load cells and one LVDT are used to monitor the force applied by each actuator and displacement of the tools.

4 REELING/STRAIGHTENING EXPERIMENTS

The bending and straightening steps as performed by the test facility are illustrated in Figure 2. When the actuators move forward, the pipe is bent over the bending die. Similarly, the pipe is straightened when the actuators move back slightly beyond their original position. In all experiments, the radii of curvature of reeling and straightening tools were 6 m and 30 m, respectively.



(a) (b)

(c)

Figure 2: Sequence of Pipe Deformed Configurations during Bending/Straightening Test

The pipe samples were assembled in the facility so to have its minimum diameter plane, determined from the mapped surfaces, coincident with the angular position of maximum tensile longitudinal bending strains in the cross-section (henceforth denominated bending plane).

The average diameters and maximum ovalization of pipes before and after reeling/straightening tests are giving in Table 3. Although the mean values of diameters (*D*) underwent an insignificant change, the ovalization (Δ_o) of the bent samples increased considerably. Values of Δ_o that were between 0.194% and 0.295% in intact condition shifted to values ranging from 0.558% and 0.729%. Therefore the ovalization increased in average of 0.00426.

Sample	*D* (mm)	Δ_o (%)	D_a (mm)	Δ_{oa} (%)
T1A	219.89	0.239	219.81	0.558
T1B	219.61	0.205	219.69	0.729
T2A	219.50	0.205	219.87	0.694
T2B	220.01	0.295	219.82	0.672
T3A	219.56	0.194	219.66	0.615
Average	219.71	0.228	219.77	0.654

Table 3: The average Diameters and Maximum Ovalizations of Pipes Before and After Reeling/Straightening

5 COLLAPSE EXPERIMENTS

The reeled and intact samples were prepared (Figure 3) to be collapsed under external pressure (Figure 4). All the details of samples preparation and tests are clearly showed in Pasqualino et al., 2004

Figure 3: Detail of the End Plug

The experimental collapse pressure (P_{co}), the D/t ratio and the samples ovalization (Δ_0 for intact and Δ_{0a} for reeled condition) are reported in Table 4. At a first glance, it seems that the difference in initial ovalizations have not affected significantly the collapse pressure, because the average value of the intact samples (T3B, T3C and T3D) was approximately equal to 8,900 psi while the reeled samples resulted in an average value of 9,000 psi. Considering that the samples had quite the same D/t ratio, if the ovalization would drive the collapse pressure, the average result of the reeled samples would be significantly less than 8,900 psi

On the other hand, a more careful investigation will make us to conclude that a combination between ovalization and initial hardening may have resulted in higher values for the collapse pressure of the reeled pipes. From the experimental tests, the increased ovalization was compensated by the strain-hardening of X-60 steel to keep the collapse pressure practically unaltered by the reeling installation process. From Table 2, it can be verified that although the average ratio σ_0/σ_u was equal to 0.96 to the axial samples, the same ratio was equal to 0.76 to the hoop ones. Then much more hardening seems to occur in hoop direction and it can strongly increase the collapse pressure of the reeled samples compensating the decrease caused by higher initial ovalizations.

Figure 4: Collapsed Sample

Sample	Δ_o (%)	Δ_{oa} (%)	D/t	P_{co} (psi)	P_{co} (MPa)
T1A	0.239	0.558	14.48	9,120	62.88
T1B	0.205	0.729	14.82	8,569	59.08
T2A	0.205	0.694	14.67	9,302	64.14
T2B	0.295	0.672	14.97	8,626	59.47
T3A	0.194	0.615	14.55	9,396	64.78
T3B	0.306	-	14.66	8,811	60.75
T3C	0.205	-	14.83	8,935	61.60
T3D	0.182	-	14.69	8,976	61.89

Table 4: Results of Collapse Pressure Experiments

6 THEORETICAL ANALYSIS

The experimental procedure as a whole (reeling, unreeling and collapse) was numerically simulated using a three-dimensional nonlinear finite element model with the aid of the software ABAQUS 6.9.

To transfer the geometry data of the pipe samples to ABAQUS, allowing the generation of the FE meshes, a FORTRAN program was developed. The geometric values (diameter and thickness) measured along nine pipe sections during experimental phase (Pasqualino et al., 2004) were used as input in other to represent the initial imperfections around pipe perimeter. The program gives as output the coordinates (x, y, z) of each node and its connectivity under quadrilateral solid elements, using linear interpolation between cross-sections measured values (diameter and thickness). Solid elements (C3D8) with eight nodes and three degree of freedom per node (three translational) were used.

The finite element mesh was generated with five elements in radial direction and forty elements in hoop direction (one element each 9 degrees), as presented in Figure 5. The longitudinal mesh was made with two different refinements, being the more refined one between the nine cross-sections (central region of the pipe) measured in experimental phase. In this area, there are a total of forty longitudinal elements, five for each 200 mm of pipe, as shown in Figure 6. The region away from the center, which is not the interest of the study, was generated using the average values of diameter and thickness of each pipe (Table 1), and has a total of sixty eight elements for a length of 3.6 m.

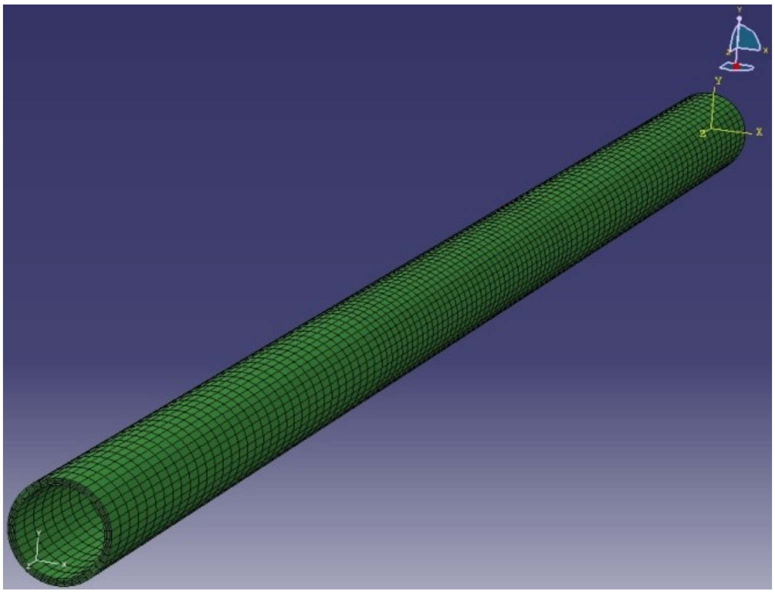


Figure 5: Finite Element Mesh of Pipe

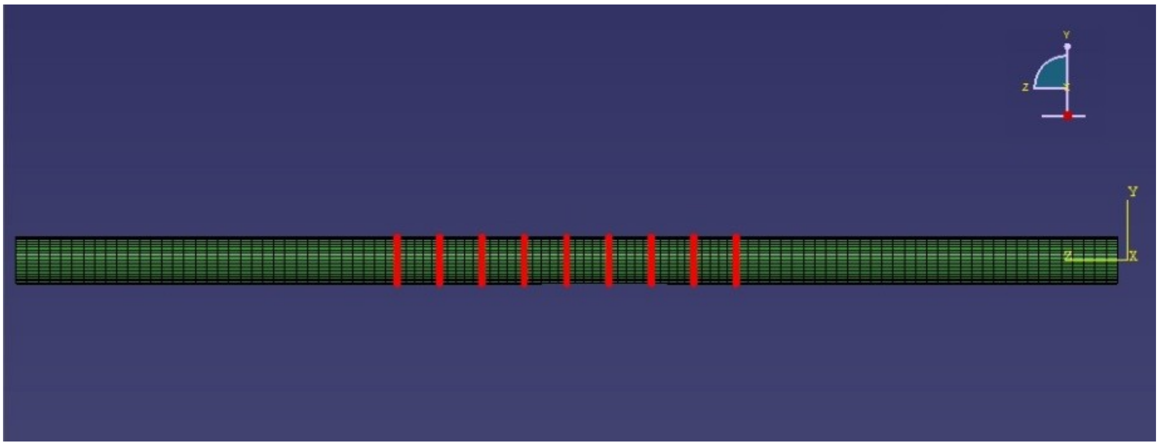


Figure 6: Longitudinal Finite Element Mesh

The two die tools of the bending simulator were modeled as analytical surfaces, controlled by reference nodes. Contact surfaces were generated to simulate the contact forces between the analytical surface and the external faces of the pipe model. The reeling/straightening process was simulated through the motion of the analytical surfaces in the bending plane (direction *y*) of each pipe. The hydrostatic pressure was applied with the aid of surface loads.

The nodes of the pipe edge were coupled to a reference node located at a distance of 850 mm from the edge of the tube, so as to represent the interactions between the pipe and the roller assembly of the bending simulator. This kinematic coupling constrain makes the set of nodes follow the motion of the reference node as a rigid body. This reference node was encastred, but let free to rotate around axis *x* and translate in *z*.

A total of five steps were created in ABAQUS to simulate precisely all the experimental procedure. The first three steps were responsible for bending (Figure 7), straightening (Figure 8) and spring back (Figure 9), respectively. The total forces generated by the hydraulic actuators during tests were used to calibrate the move forward and move back of the die tools.

The last two steps (prescribed value and Riks) simulated the applied hydrostatic pressure at the pipe central region with approximately 2.0 m long. To represent the end plugs used in experimental procedure the nodes located at the corresponding positions were completely restricted in one edge and restricted only in *x* and *y* direction at the other. The hydrostatic pressure generated by the end plugs was obtained through equivalent forces applied to the edge nodes. Figure 10 shows a collapsed pipe.

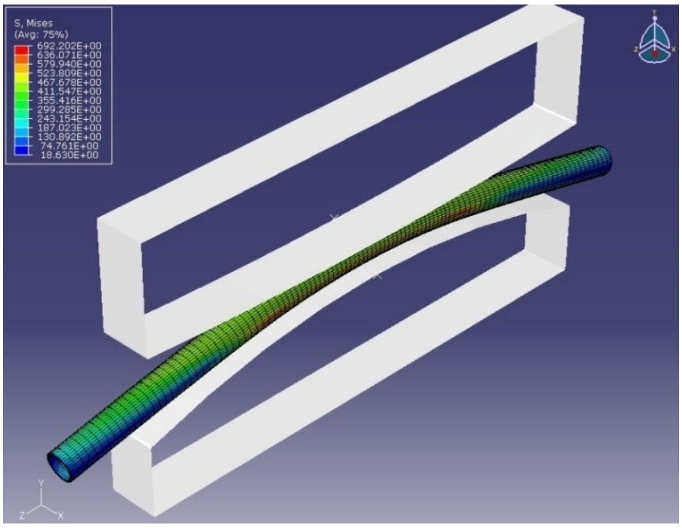


Figure 7: Step 1 – Bending the Pipe

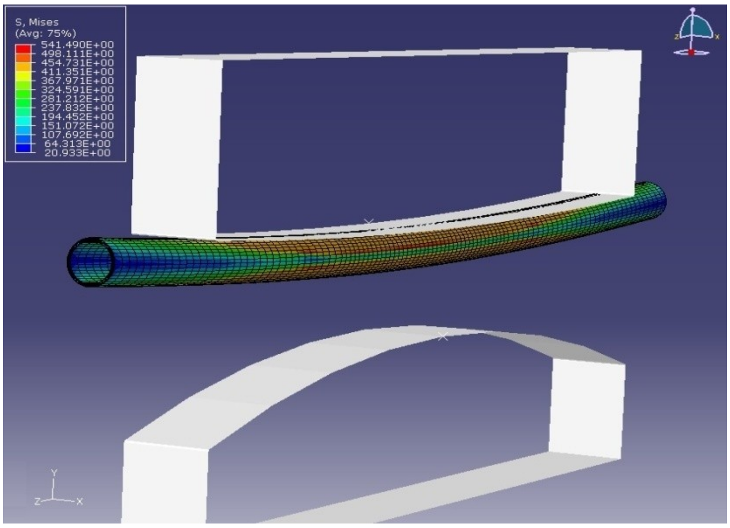


Figure 8: Step 2 – Straightening the Pipe

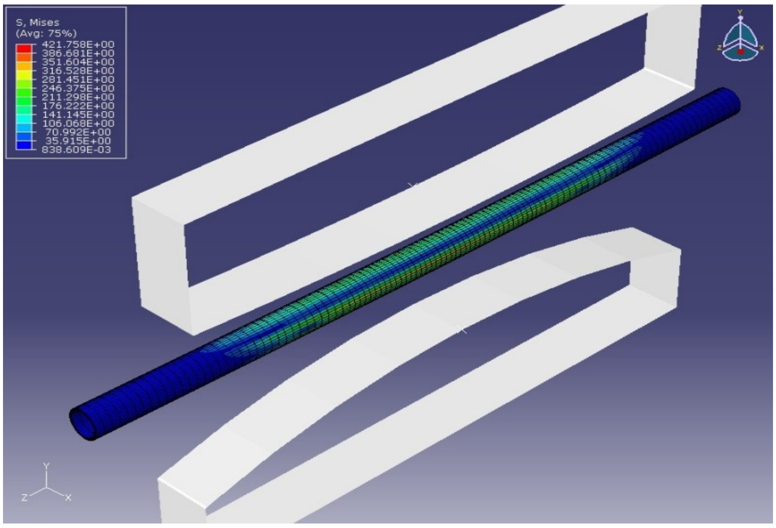


Figure 9: Step 3 – Die Tools away from the Pipe

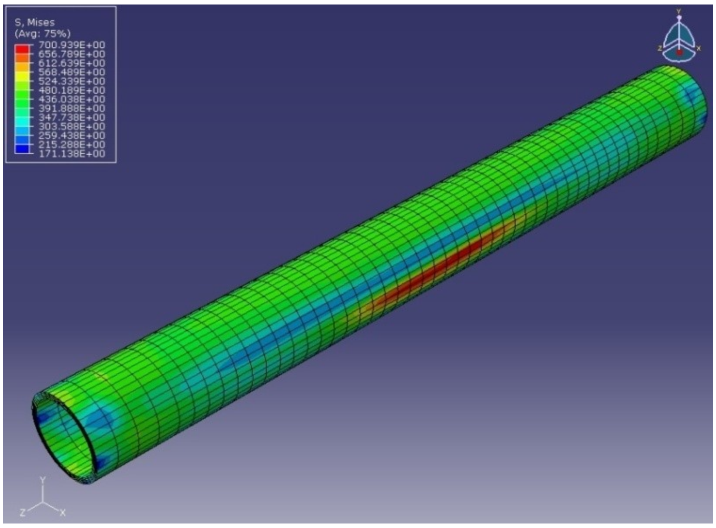


Figure 10: Collapsed Pipe at the End

Three constitutive models under the von Mises potential flow rule were simulated in ABAQUS to obtain the collapse pressure, the first model has used the axial material properties and isotropic hardening ($P_{co'}$), the second has employed the same properties but combined isotropic and kinematic hardening ($P_{co''}$) and the third has used the combined hardening model but with the hoop properties ($P_{co'''}$). All of them simulated the reeling and unreeling process followed by hydrostatic pressure. The numerical and experimental results are compared in Table 5, where the variable ε represents the scattering between the predicted collapse pressure and the experimental value.

Considering the three employed constitutive models for the reeled samples, the one that best correlated the experimental results was Model 2, with combined hardening and the axial properties. Most of the plasticity generated during the reeling and unreeling process occurs in axial direction and the kinematic hardening is crucial to represent the reverse load and to account for the Bauschinger effect. The same analyses using the hoop properties confer much more hardening to the samples (Table 2), which increase the collapse pressure $P_{co'''}$.

In relation to the collapse analyses of the intact samples (T3B, T3C and T3D) the correlation was under the expectations for the constitutive models employed. The discrepancies can be explained by the way the initial ovalizations were provided to the FE mesh. Collapse analyses of intact structures are very sensitive to initial imperfections and the correct load of instability is only detected if some kind of smooth function of the imperfections magnitude is simulated. In general, such kind of collapse analyses are carried out using a function of the maximum ovalization measured through the samples mapping. In this case the FE meshes were generated using directly the measured diameters. Such kind of functional approach for the initial ovalizations will be used to improve the collapse pressure results.

	Experimental		Model 1		Model 2		Model 3	
	Sample	P_{co} (MPa)	$P_{co'}$ (MPa)	ε (%)	$P_{co''}$ (MPa)	ε (%)	$P_{co'''}$ (MPa)	ε (%)
Reeled	T1A	62.88	64.93	3.26	62.02	-1.38	61.74	-1.81
	T1B	59.08	62.38	5.58	60.06	1.65	59.73	1.10
	T2A	64.14	72.46	12.99	58.79	-8.33	71.80	11.96
	T2B	59.47	70.66	18.82	56.90	-4.34	69.95	17.61
	T3A	64.78	71.65	10.60	69.08	6.63	72.70	12.22
	Average	**62.07**	**68.42**	**10.25**	**61.37**	**-1.15**	**67.18**	**8.22**
Intact	T3B	60.75	66.80	9.95	67.72	11.47	71.02	16.90
	T3C	61.60	66.46	7.88	67.17	9.04	70.43	14.33
	T3D	61.89	67.05	8.35	67.84	9.62	71.12	14.91
	Average	**61.41**	**66.77**	**8.73**	**67.58**	**10.04**	**70.86**	**15.38**

Table 5: Comparison between Numerical and Experimental Results in Collapse Pressure

7 CONCLUSIONS

The ovalization of the large-scale pipe samples, which were between 0.194% and 0.295% before reeling, shifted to values ranging from 0.558% and 0.729% after reeling. It represents an average increase of 0.00426.

The average collapse pressure of the intact pipe samples was approximately equal to 8,900psi while the reeled samples resulted in 9,000psi. Considering that the intact and reeled pipes had almost the same *D/t* ratio, if the ovalization would drive the collapse pressure, the average result of the reeled samples would be significantly less than 8,900 psi. Therefore, the combination between ovalization and strain hardening resulted in higher values for the collapse pressure of the reeled pipes, when compared to the intact samples.

The collapse pressure of reeled pipes was accurately determined through a FE model considering the axial material properties under the elastic-plastic von Mises flow rule with combined kinematic and isotropic strain hardening.

The experimental and numerical results presented here have showed that the reeling installation method does not affect significantly the collapse pressure of the studied pipe samples. For this reason, it is recommended to carry out a comprehensive parametric study to determine collapse curves of offshore pipelines with different geometric and material parameters.

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