Collapse testing and analysis of JCO-E steel pipes

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Abstract

During deep-water pipeline installation, the pipe is subjected to high external pressure, which may trigger structural instability is the form of collapse, with catastrophic effects. Pipe resistance of against this instability is a major issue for safeguarding offshore pipeline integrity. In the present paper, the collapse resistance of steel pipes fabricated by the JCO-E pipe manufacturing process are examined. The paper describes a combined experimental, numerical and analytical work on the collapse of a 30-inch-diameter X60 JCO-E pipe. The pipe is subjected to full-scale external pressure testing that determined its collapse (ultimate) and propagation pressure. The pipe, prior to collapse, has been subjected to heat treatment at a level that represents the coating process. Prior to collapse testing, initial ovality measurements have been obtained along the pipe. Furthermore, strip specimens have been extracted from the pipe, before and after heat treatment, and the corresponding material properties have been obtained from uniaxial testing. Numerical calculations are also performed using a full-scale three-dimensional finite element model that simulates the collapse test procedure, using the real material properties from the strip specimens. The experimental data and the numerical results on collapse pressure of the pipe are compared with the predictions of the DNV-ST-F101 formula, and the value of fabrication factor α_{fab} is discussed.

1. Introduction

Thick-walled line pipes with diameter larger than 18 inches, which are candidates for deep offshore applications, are commonly fabricated by cold forming of long plates. During the installation process of deep and ultra-deep-water projects, the pipeline should sustain the high external pressure applied by the deep-sea environment. This may ovalize severely the pipe and lead to collapse with catastrophic consequences [1]. Therefore, the structural integrity of offshore pipelines against this extreme load is of major concern.

The critical (ultimate) pressure, that a pipe can sustain under external pressure, is referred to as “critical pressure” (P_c) and it constitutes of one the main limit states governing the offshore pipelines design, while this phenomenon is described in detail in several textbook (e.g., [1]). The initial length of this structural instability is limited to a few pipe diameters. However, this flattening configuration, under constant pressure, may propagate along the pipeline at high velocity, damaging a significant length of the pipeline. The minimum pressure, required to initiate the buckle propagation, is referred to as "propagation pressure" (P_{pr}) and it is significantly lower than the collapse pressure [2].

Previous experimental [3] and numerical works [4, 5, 6] have shown that large-diameter line pipes, fabricated by cold forming processes, exhibit a reduced collapse capacity with respect to seamless pipes. More specifically, it has been shown that the cold forming process affects the material properties and introduce residual stresses in the final product. During the final phase of the fabrication process, the line pipe is expanded with a mechanical expander to achieve uniform diameter of the pipe cross-section, which leads to plastic deformation of the pipe material in the circumferential direction. Therefore, the compressive strength of the pipe material in the circumferential direction is reduced, because of the Bauschinger effect. Compressive strength is a key factor for resisting high levels of external pressure, and this reduction is of major concern, for pipe structural integrity.

It is possible to alleviate the material strength degradation with heat treatment of the line pipe. Previous experimental tests [3, 7, 8, 9] have shown that even a mild heat treatment process up to $250°C$ temperature leads to recovering the compressive hoop strength, which also results in higher collapse capacity of the pipe. This heat treatment could be imposed to the pipeline during typical coating with epoxy for corrosion protection and thermal insulation.

The present paper mainly focuses on numerical results, which are based on the results of a full-scale test on a thick-walled JCO-E pipe. The full-scale collapse test has been performed by C-FER Technologies Inc. ("C-FER") in Edmonton, Alberta, Canada, on a 30-inch-diameter thick-walled pipe made of X60 steel grade. Prior to collapse testing, the pipe specimen has been thermally treated at a level and duration similar to the one imposed by the typical coating process. In addition, geometric measurements have been obtained along the pipe to determine the initial cross-sectional ovality along the specimen. Subsequently, the pipe specimen was inserted into the C-FER's deep-water experimental chamber, and the collapse (ultimate) pressure and the propagation pressure of the pipe have been measured. The full-scale test of the heat-treated steel pipe is numerically simulated, using finite element program ABAQUS/Standard. The numerical results are compared with the experimental results, in terms of both collapse and propagation pressure, using the material data before and after heat treatment.

2. Experimental Testing

The primal purpose of the experimental work was to quantify the collapse resistance of pipes produced by the JCO-E process. The experimental program involves primarily a full-scale collapse test to examine the collapse resistance of a 30-inch-diameter thick-walled pipe made of X60 grade steel at C-FER testing facilities. The pipe specimen was heated to moderate temperatures, similar to the typical heating cycle applied during the coating process. In addition, a series of monotonic uniaxial tests on strip specimens extracted from the pipe (before and after heat treatment) were performed, so that the material properties of the fabricated line pipe are obtained in terms of stress-strain curves.

2.1 Full-scale collapse testing

The collapse test of the 30-inch-diameter pipe was conducted in C-FER's Deepwater Experimental Chamber (DEC), which has an inside diameter of 1.2m and a total inside length of 10.3m. This chamber has been extensively for numerous tests in the past. The tested, maximum pressure capacity of the chamber is of 9000 psi. The measurement of all instruments associated with the experiment, is performed by using state-of-the-art computer, software, and signal equipment. The experimental instruments used, consist of pressure transducers and water volume waters. The data acquisition analysis is performed by using a computer equipped with LabVIEW software package.

The 10-diameter-long pipe specimen was inserted into the experimental chamber, where hydrostatic pressure was applied on the external surface of the pipe. Prior to testing, geometric measurements were performed on the specimen. In the circumferential and longitudinal directions, the pipe specimen was marked onto 16 locations and 9 stations respectively, and a grid composed of 144 points was created as shown in Figure *1* for the circumferential marking. Thus, the outer diameter (D_o) and the wall thickness (t) were measured. The outer diameter is quantified along the length of the pipe, using a calibrated micrometer, and the minimum, maximum and average values of D_o are acquired from these measurements. Ovality (Δ) measurements are also acquired from these measurements, using the following expression that describes ovality:

$$\Delta = \frac{D_{o,max} - D_{o,min}}{D_{nom}} \quad (1)$$

where D_{nom}, is the nominal outer diameter, $D_{o,max}$ is the maximum measured outer diameter, and $D_{o,min}$ is the minimum measured outer diameter. Wall thickness measurements are obtained using a calibrated ultrasonic probe, and measurements of total pipe length and circumference are also taken. Table *1* presents the results of the geometric measurements. The full-scale pipe specimen used for testing, had already been thermally treated at a level of a coating process.

The specimen was placed inside the experimental chamber, using welded-end caps to the pipe specimen. Subsequently, the chamber was filled with water, and pressurized at a rate determined by a pump so that the specimen was subjected to progressively increasing external pressure, until collapse occurs. The pressurization has been further continued, so that the collapse pattern propagates along the specimen length, and the propagation pressure is measured. Using the data acquisition software described above, specimen internal pressure, chamber pressure and volume of water were recorded during test.

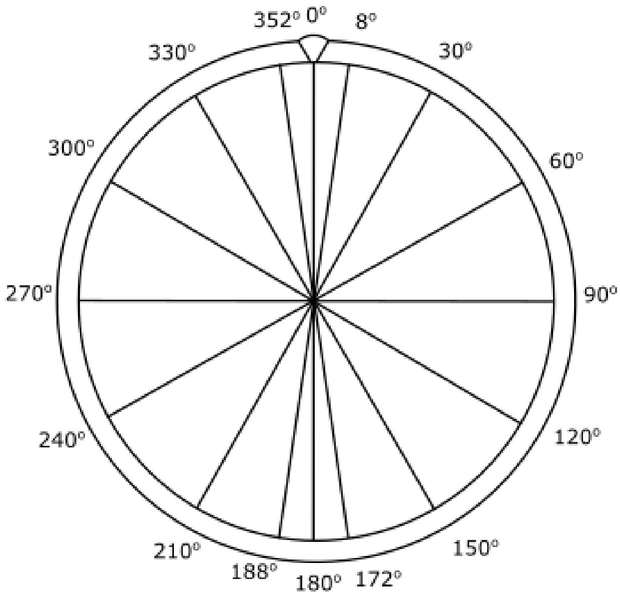


Figure 1. Measurement stations on surface of the pipe specimen.

Table 1. Prior to collapse test measurements.

Specimen 30-Inch OD (T08511-9)	
Wall Thickness Measurements	
Maximum Wall Thickness(mm)	38.61
Minimum Wall Thickness (mm)	37.90
Average Wall Thickness (mm)	38.29
Diameter Measurements	
Maximum Diameter (mm)	762.0
Minimum Diameter (mm)	760.6
Average Diameter (mm)	761.4
Ovality Measurements	
Maximum Ovality (%)	0.162
Minimum Ovality (%)	0.069
Average Ovality (%)	0.103
Pipe Length and Circumference	
Average Length (mm)	7635
Average Circumference (mm)	2395

2.2 Material properties testing

The material properties of the line pipe specimen were evaluated experimentally, and the effectiveness of the heat treatment process was examined in terms of the strength recovery obtained in the compressive strength. Strip specimens were cut out of the heat treated and the non-heat treated JCO-E pipe, provided by the mill. Using a methodology similar to the one reported in [4, 5, 6], longitudinal and circumferential strip specimens were extracted from the outer and the inner parts of the pipe wall. More specifically, the specimens were extracted at the 90-degree and 270-degree positions around the circumference (see Figure *1*).

The coupon specimens were tested in tension and compression; the tests were conducted at University of Thessaly, using the material testing machine shown in Figure *2*. For the compression tests, an anti-buckling device was attached to the specimens to prevent buckling of the specimen. The coupons were placed between the two platens, as shown in Figure *2*. During tension and compression testing, an extensometer with gauge length of 10mm was used.

Stress-strain material curves in tension and compression were obtained from coupons that were machined from specimens extracted from the JCO-E pipes. Figure *3a* presents compressive stress-strain curves in the circumferential direction at the inner and outer surface at 90 degrees position, while *Figure 3b* presents the hoop compressive stress-strain curves at 90 degrees and 270 degrees positions of the outer surface before and after the heat treatment to evaluate the effect of moderate temperatures on compressive hoop strength of the pipe material. The yield stress at 0.5% engineering strain of the X60 steel material at the outer surface of the pipe at 90-degrees and 270-degrees before the heat treatment equal to 472 MPa and 458 MPa, respectively. After heat treatment at moderate temperature levels, the corresponding yield stress values are 493 MPa and 489 MPa, which correspond to compressive strength increase by 4.5% and 6.8%, respectively.

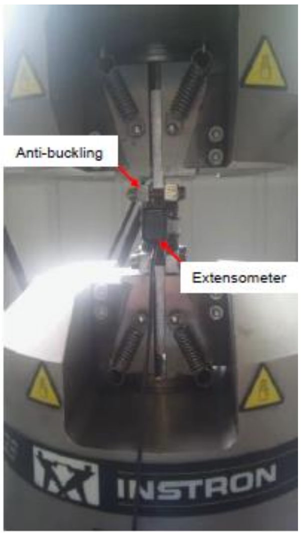
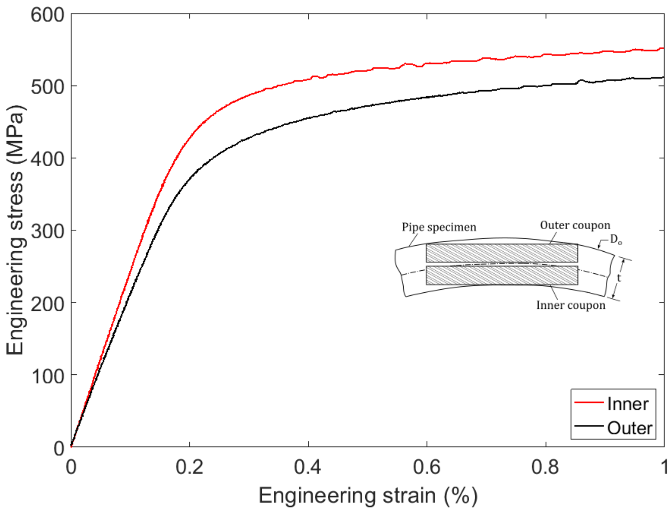
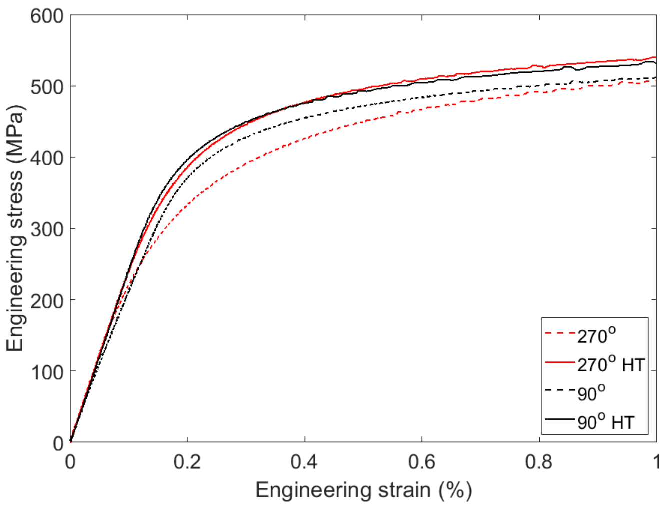


Figure 2. (a) Machine of material testing of coupon specimens at University of Thessaly *[10]*.



(a)



(b)

Figure 3. Compressive stress-strain curves at the circumferential direction (a) at 90 degrees at inner and outer surface before heat treatment, (b) at 90 and 270 degrees at the outer surface before and after heat treatment.

3. Description of numerical model

The numerical simulations were conducted using general-purpose finite element package ABAQUS/Standard [11]. The analysis accounts for geometric non-linearities of the line pipes, whereas the X60 material of the 30-inch-diameter pipe is considered through elastic-plastic J_2 (von Mises) plasticity model with isotropic hardening. The model, shown in Figure *4*, is capable of simulating the collapse of the line pipe. The model is five outer diameters long ($L = 5D_o$), simulating half of the pipe segment tested in C-FER. The analysis considers a quarter of the cross section of the line pipe using symmetry with respect to the *x-z* and *y-z* planes, as shown in Figure *4*. In addition, *x-y* plane symmetry is assumed in the $z = 0$ plane representing the ten diameters specimen, described in Section 2.1, allowing only in-plane motion on the corresponding nodes, while in the $z = L$ plane the model is fixed to represent the boundary conditions of the experimental test.

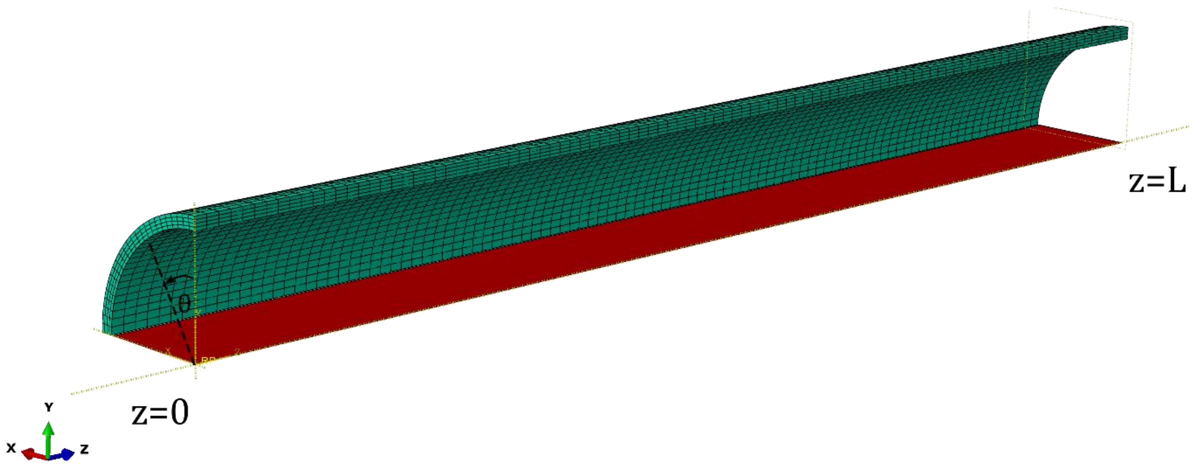


Figure 4. Three-dimensional numerical model of the 30-inch diameter line pipe.

The thick-walled pipe is modelled with 20-node reduced-integration solid elements (C2D20R). The quarter of cross-section contains twenty-five elements, there are one hundred elements in the longitudinal direction of the pipe, while four elements are considered through the wall thickness. The geometrical properties of the numerical model are based on the average measurements presented in Table *1*. The outer diameter (D_o) and the wall thickness (t) of the pipe are equal to 761.4mm and 38.29mm, respectively, and the half-length (L) of the numerical model is 38,175mm. The cross-section at the fixed end ($z = L$) is considered as a quarter of a perfect circle, following the average outer diameter and wall thickness values presented in Table *1*, while the cross-section of the model at the symmetry plane ($z = 0$) has an initial ovality equal to $\Delta = 0.21\%$, which is slightly higher than the maximum measured ovality.

Previous works [4] have shown that the circumferential compressive strength governs the collapse capacity of lined pipes under external pressure. Furthermore, the material of the pipe at the outer surface presents lower compressive hoop strength than the inner surface, as shown in Figure *3a*, due to higher tensile loads during the cold forming process and the expansion phase. Therefore, the stress-strain curves at the outer surface before and after the heat treatment, presented in Figure *3b*, are considered in the present analysis to examine collapse pressure recovery. Table *2* summarizes the material properties of the circumferential compressive stress-strain curves at 90-degree and 270-degree locations before and after the heat treatment, where σ_y is the yield stress at 0.5% engineering strain, E is the Young's modulus, and ν is the Poisson's ratio, while the table presents an increase by 4.5% and 6.8% of the yield stress in the material curves at 90 degrees and 270 degrees locations, respectively, after the heat treatment. The corresponding collapse capacity recovery is presented in the following section.

Finally, an analytical surface is developed at *x-z* plane ($y = 0$), as depicted in Figure *4*, to restrict the translation of the cross-section of the pipe at $\theta = 0$ location through the negative direction of *y*-axis, simulating the contact of the upper side of the cross-section with lower side, during collapse and buckle propagation. A frictionless surface-to-surface interaction is assumed, considering as "master" surface the upper surface of the rigid body and as "slave" surface the inner surface of the pipe, while the "Direct" method for hard pressure-overclosure behaviour is applied.

Table 2. Material properties of X60 steel pipe specimen at 90- and 270-degrees locations at the outer surface before and after heat treatment.

	σ_y (MPa)	E (GPa)	ν
90°	472	207	0.3
90° HT	493		
270°	458		
270° HT	489		

4. Numerical results and comparison with experimental data

Collapse and buckle propagation of the 30-inch diameter pipe specimen is simulated using the finite element (FE) model described in the previous section. Initially, the numerical results are compared with those obtained by the experiment performed at C-FER, using the experimental stress-strain data obtained from the heat-treated specimen. Subsequently, numerical results are presented using the same model, considering the material properties before heat-treatment, so that the effects of collapse strength recovery are illustrated.

Figure *5* presents the equilibrium path of the applied external pressure, normalized by the yield pressure of the pipe ($P_y = 2\sigma_{y,n}\, t/(D_o - t)$, where $\sigma_{y,n}$, D_o and t are the nominal yield stress of X60 steel material, outer diameter and wall thickness of the 30-inch-diameter pipe), with respect to the volume change enclosed by the pipe, normalized by the initial pipe volume (V_o), considering perfect geometry. The results are obtained using the material properties of X60 steel pipe specimen at the 270-degree location and at the outer surface, after the heat treatment shown in *Figure 3b*. The numbers on the diagram correspond to the deformed configurations of the finite element model, as shown in Figure *6*. The pressure rises until a maximum pressure value "stage (1)", which represents the collapse pressure, i.e., the maximum pressure that the structure can sustain upon external pressurization. Soon after collapse, the structure softens, due to the formation of four-equally spaced "plastic hinges" around the circumference of the collapsed cross-section that drive post-collapse deformation and enable the formation of a plastic mechanism [2, 12, 13]. The reduced stiffness of the structure after collapse, results in a significant reduction of pressure "(2)" in the post-buckling regime until a minimum pressure value "(3)" is reached, which corresponds to the first contact of two opposite locations of the collapsed cross-section. Subsequently, a small increase in pressure is observed from "(3)" to "(4)" in Figure *6*. Then, the buckle starts propagating along the pipe under constant pressure, as shown in the deformed configuration "(5)".

The numerical results show very good agreement with the experimental results, in terms of collapse pressure. The experimental collapse pressure for the 30-inch-diameter pipe is equal to 43.4 MPa, and the corresponding numerical value is 42.9 MPa, considering the compressive stress-strain curve at 270-degree location from the outer surface after heat treatment (Figure *3b*).

An additional numerical model is considered assuming a pipe length equal to fourteen outer diameters, which is able to describe the steady state deformation during buckle propagation, as reported in previous works [2]. The current numerical model is similar to the one depicted in Figure *4* (and described in detail in section 3) in terms of boundary conditions and stress-strain material curve. Figure *7* depicts the equilibrium path of the applied external pressure, normalized by the yield pressure of the pipe, plotted against the volume change, which is normalized by the initial volume of the pipe Figure *8* shows the corresponding deformed configurations of the pipe. The equilibrium path is similar to the one described for the five diameters length model, which is presented in Figure *5*. However, after the gradual increase of the external pressure from stage "(3)" to stage "(4)", a steady state is reached, where the buckle propagates along the pipeline under constant external pressure "(5)" against the volume change of the pipe. Considering this long numerical model, the propagation pressure is computed equal to 9.4 MPa, which is in very good agreement with the experimental value reported from C-FER (9.1 MPa).

The compressive circumferential stress-strain curve at the 270-degree location at the outer surface of the "as fabricated" pipe (before heat treatment), depicted in Figure *3b*, is considered as representative material curve for computing the collapse capacity of the "as fabricated" pipe. In this case, there no experimental value for the collapse pressure.

Figure *9* presents the variation of applied external pressure in terms of volume change for the "as fabricated" and the "heat treated" pipes. The corresponding values of collapse pressure are 36.8 MPa and 42.9 MPa respectively, which indicates a 16% increase due to heat treatment. The collapse pressure is also computed considering the stress-strain curve at the 90-degree location at the outer surface of the pipe after heat treatment, is also 42.9 MPa. Considering the material properties at the same location from the "as fabricated" pipe, the collapse pressure is computed equal to 39.7 MPa. These results indicate an 8% increase of collapse pressure because of heat treatment. Table *3* summarizes the numerical results, in comparison with the experimental test.

The above numerical and experimental values of collapse pressure are compared with the corresponding predictions of the DNVGL-ST-F101 standard [14]. According to the design standard, the collapse pressure can be estimated by the following equation:

$$(P_c - P_{el})\left({P_c}^2 - {P_p}^2\right) = P_c P_{el} P_p O_0 \frac{D_o}{t} \qquad (2)$$

where P_c, P_{el} and P_p are the collapse pressure, elastic collapse pressure and plastic collapse pressure, which are given by the following expressions:

$$P_{el} = \frac{2E\left(t/D_o\right)^3}{1-\nu^2} \qquad (3)$$

$$P_p = \sigma_y \alpha_{fab} \frac{2t}{D_o} \qquad (4)$$

In the above expressions, E, D_o and t are the Young's modulus, outer diameter and wall thickness of the pipe respectively, while σ_y is the yield stress, O_0 is the initial cross-sectional ovality of the pipe, which is equal to Δ defined in equation (1), and α_{fab} is a fabrication factor, which accounts for the degradation in the mechanical properties due to the cold forming process. For JCO-E pipes a specific value of α_{fab} is not defined. Therefore, the value of α_{fab} is taken equal to 0.85, which is the value for UOE pipes specified by DNVGL-ST-F101. The standard also states that the α_{fab} value may be increased in the case of heat treatment. Therefore, for comparison purposes, the collapse pressure for the "heat-treated" pipe is also calculated assuming $\alpha_{fab} = 1$. For the "heat treated" pipe and the "as fabricated pipe", the yield stress value (σ_y) used in Equation (4) is the mean value measured at the 90- and 270-degree locations, presented in Table *2*. Finally, according to DNVGL-ST-F101, a minimum value of ovality $O_0 = 0.5\%$ should be used.

For the "as fabricated pipe", DNVGL-ST-F101 predicts collapse pressure equal to 35.1 MPa, which is a reasonable prediction, yet somewhat lower than the corresponding finite element predictions. The DNVGL-ST-F101 collapse pressure for the case of the "heat treated" pipe is 41.5 MPa, which is also somewhat lower than the corresponding numerical predictions. and the experimental value. Finally, comparison of the collapse pressure results in Table *3* shows that the assumption of $\alpha_{fab} = 1$ provides better, yet somewhat conservative, prediction for the collapse pressure of the "heat-treated" pipe.

Table 3. Collapse pressure (in MPa) of the 30-inch diameter X60 pipe; experimental value, numerical results and DNVGL-ST-F101 [14] predictions.

Numerical Simulations				**Experimental Test (HT)**	**DNVGL $\alpha_{fab} = 0.85$**	**DNVGL (HT) $\alpha_{fab} = 1$**
90º	**90º HT**	**270º**	**270º HT**			
39.7	42.9	36.8	42.9	43.4	35.1	41.5

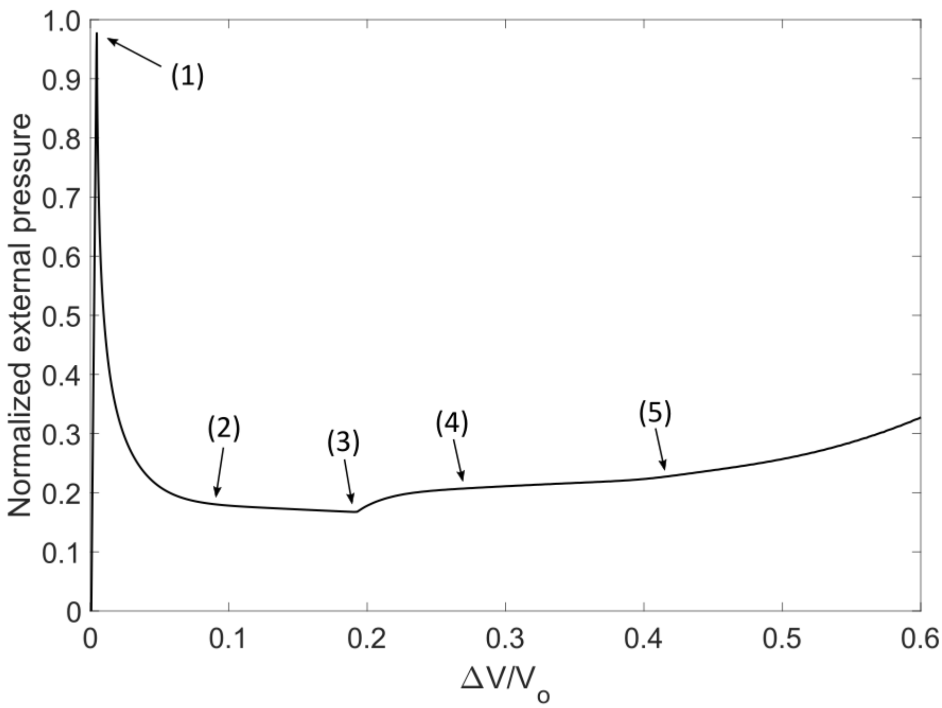


Figure 5. Normalized external pressure variation with respect to the volume change of the "heat treated" pipe; simulation of the C-FER experiment.

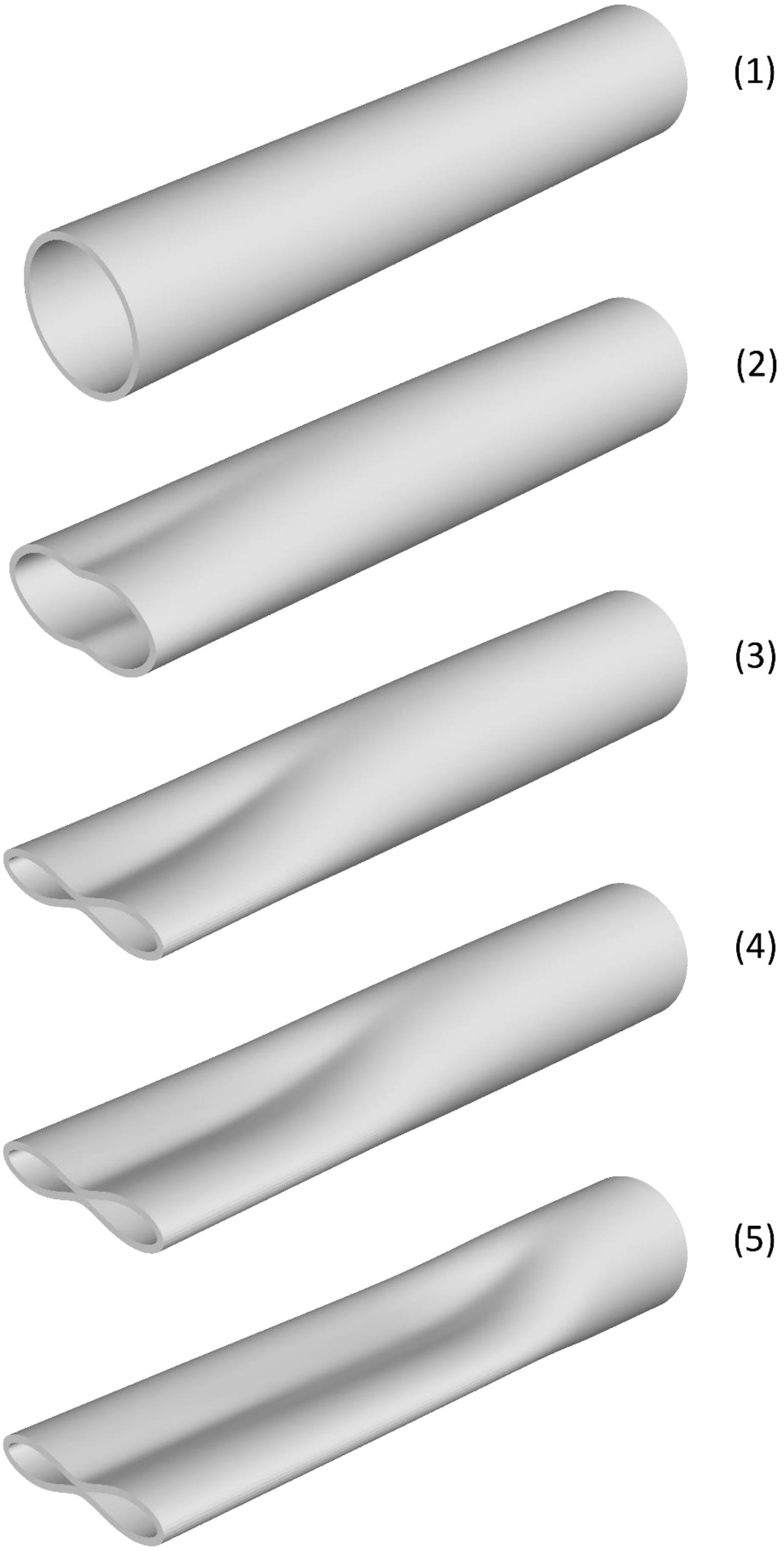


Figure 6. Sequence of deformed pipe deformation from the stage of maximum pressure to buckling propagation; the configuration numbers refer to the corresponding points on the pressure-volume diagram in Figure 5.

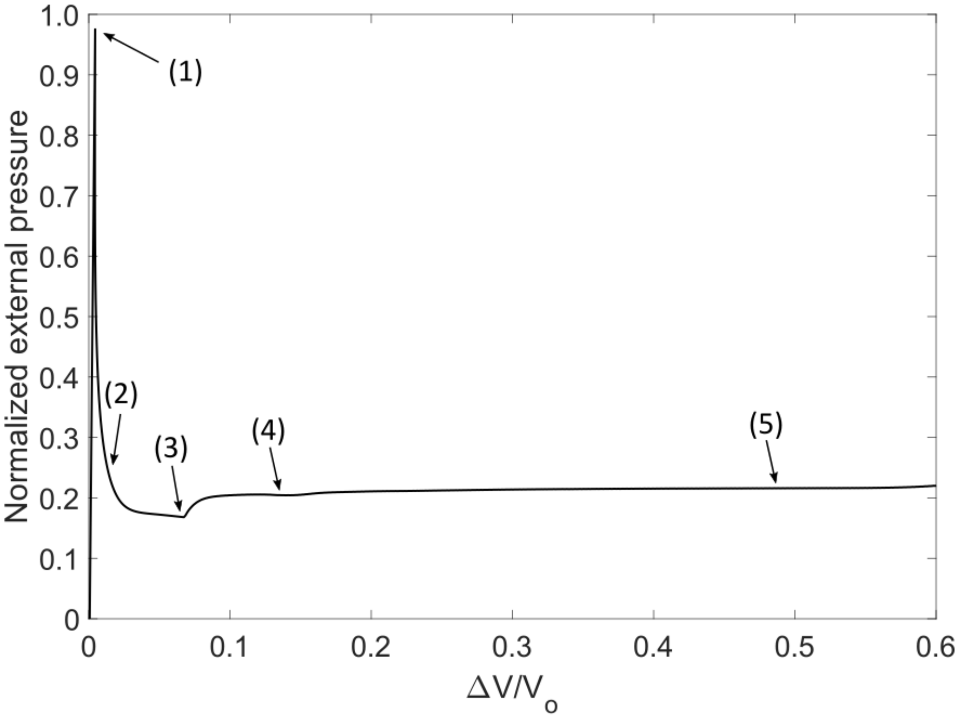


Figure 7. Normalized external pressure variation with respect to the volume change of the “heat treated” pipe, considering a fourteen-diameter-long model.

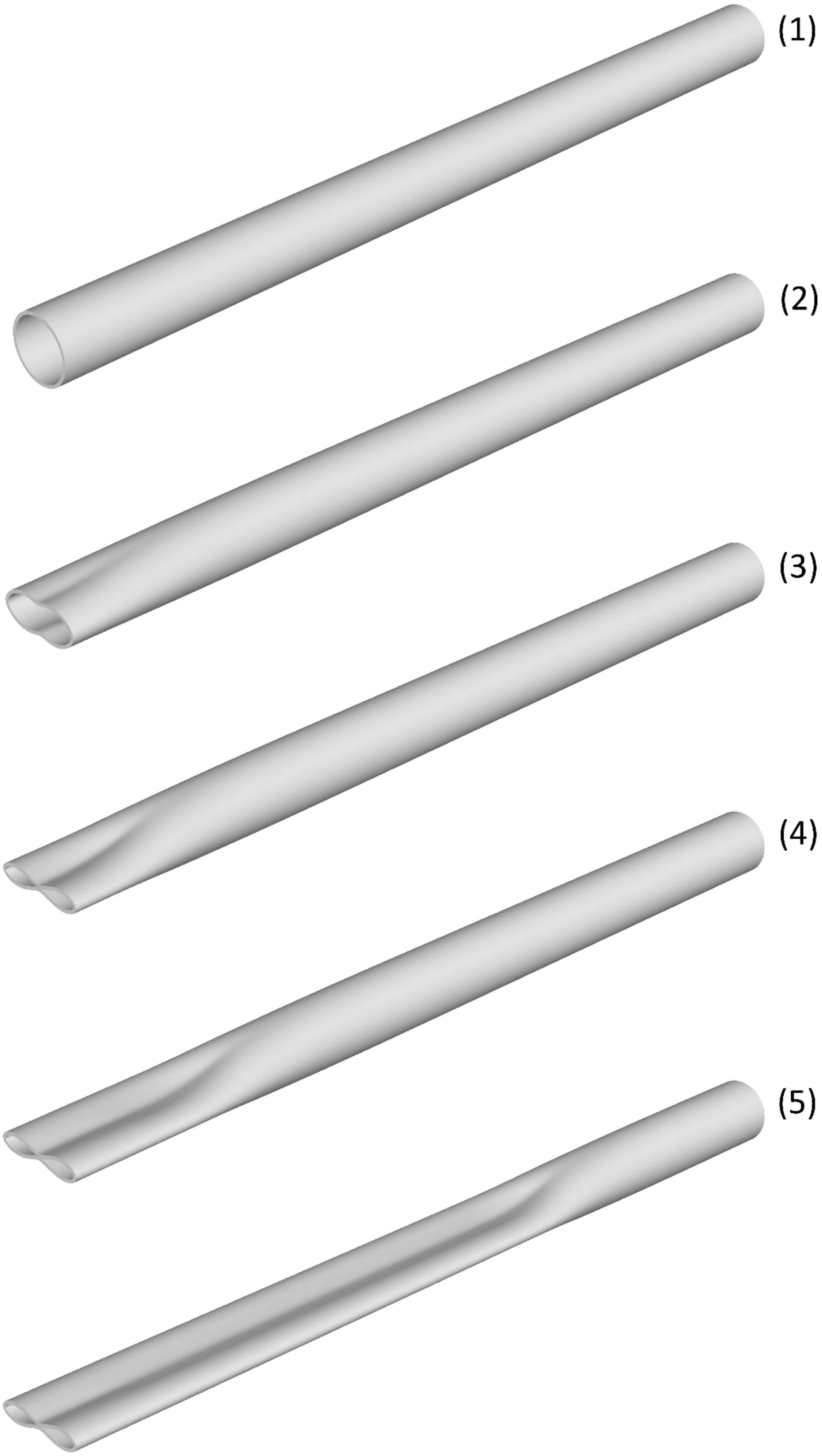


Figure 8. Sequence of deformed pipe deformation from the stage of maximum pressure to buckling propagation; the configuration numbers refer to the corresponding points on the pressure-volume diagram in Figure 7.

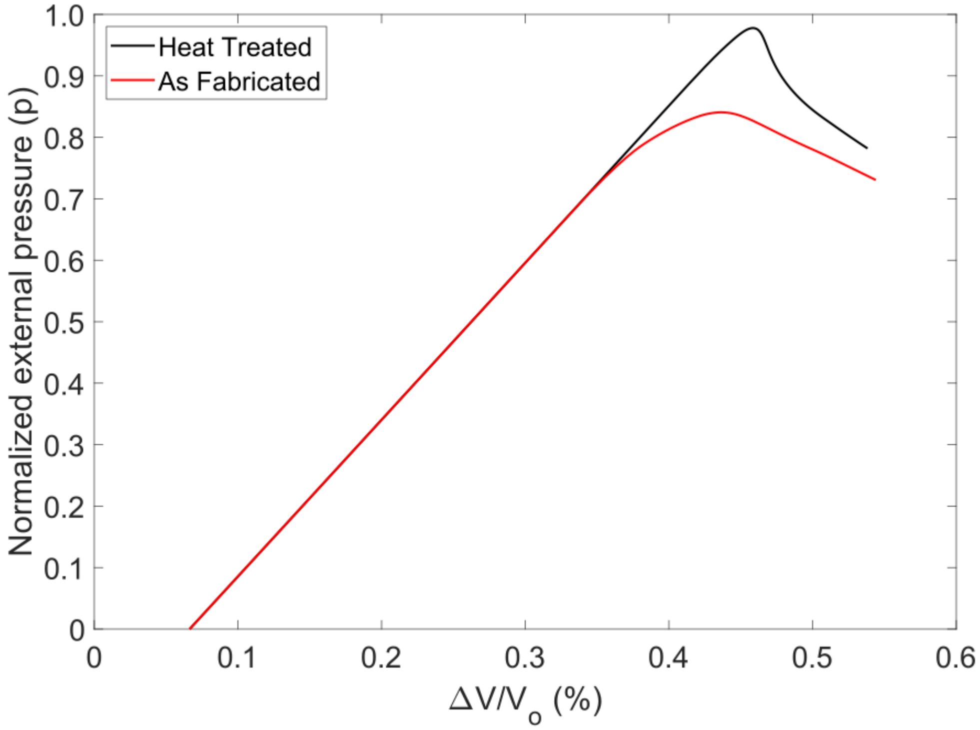


Figure 9. Variation of external pressure with respect to the volume change enclosed by the deforming pipe; “as fabricated” pipe versus “heat treated” pipe.

5. Conclusions

The purpose of the current work is to evaluate the collapse resistance of line pipes manufactured by the JCO-E process, considering the degradation of material strength due to the cold forming process, and examine the effect of mild heat treatment (corresponding to coating process) on the recovery of pipe collapse capacity. Initially, the heat treatment is shown to increase the compressive circumferential strength of the line pipe material, which is significantly affected by the cold forming fabrication of the line pipe. After performing coupon tests from pipe material extracted before and after heat treatment, it is shown an increase of 4.5% and 6.8% in the circumferential compressive yield stress, at the 90-degree and 270-degree locations, respectively.

Considering for the stress-strain curves obtained from the material tests, a three-dimensional finite element model is developed, and very good results are obtained in terms of collapse and propagation pressure in comparison with experimental value. The results also indicate that using the circumferential compressive stress-strain curves at the outer surface of the pipe, results in good predictions of the collapse capacity of the pipe.

Additional analyses are performed, using the compressive stress-strain material curves of the “as fabricated” pipe. Comparison with the “heat treated” pipe shows that the collapse capacity of the line pipe could be increased up to 16% because of heat treatment.

Finally, the numerical and experimental results of the collapse pressure are compared with corresponding predictions of the DNVGL-ST-F101 collapse formula. Using a fabrication factor equal to 0.85 due to cold forming process, the DNVGL-ST-F101 prediction is very conservative when compared with the collapse pressure values of the numerical simulations and the experimental test for the “heat treated” line pipe. When a fabrication factor equal to unity is used, more realistic yet somewhat conservative estimates of collapse pressure are obtained, in terms of the numerical and the experimental results.

References

[1] S. Kyriakides and E. Corona, *Mechanics of offshore pipelines*: volume 1 buckling and collapse, Oxford, UK: Elsevier, 2007.

[2] S. Kyriakides and L.-H. Lee, Mechanics of Offshore Pipelines, Volume 2: Buckle Propagation and Arrest, Gulf Professional Publishing, 2020.

[3] P. R. Stark and D. S. McKeehan, "Hydrostatic collapse research in support of the Oman India gas pipeline," in *Offshore Technology Conference*, Houston, USA, 1995.

[4] S. Kyriakides, E. Corona and F. J. Fischer, "On the effect of the UOE manufacturing process on the collapse pressure of long tubes," in *Offshore Technology Conference*, Houston, USA, 1991.

[5] M. D. Herynk, S. Kyriakides, A. Onoufriou and H. D. Yun, "Effects of the UOE/UOC pipe manufacturing processes on pipe collapse pressure," *International Journal of Mechanical Sciences,* vol. 49, no. 5, pp. 533-553, 2007.

[6] K. Antoniou, G. Chatzopoulou, S. A. Karamanos, A. Tazedakis, C. Palagas and E. Dourdounis, "Numerical Simulation of JCO-E Pipe Manufacturing Process and Its Effect on the External Pressure Capacity of the Pipe," *Journal of Offshore Mechanics and Arctic Engineering,* vol. 141, no. 1, p. 011704, 2019.

[7] D. DeGeer, C. Timms and V. Lobanov, "Blue stream collapse test program," in *Proceedings of OMAE2005 24th International Conference on Offshore Mechanics and Arctic Engineering*, Halkidiki, Greece, 2005.

[8] F. Arroyo, R. F. Solano, L. Mantovano, F. B. de Azevedo, H. Alves, D. Swanek, R. Silva and H. Ernst, "Qualification of UOE SAWL Linepipes with Enhanced Collapse Resistance for Ultra Deepwater Applications," in *Proceedings of the ASME 2013 32nd International Conference on Offshore Mechanics and Arctic Engineering*, Nantes, France, 2013.

[9] Y. Shinohara, T. Hara, E. Tsuru, H. Asahi, Y. Terada and N. Doi, "Change of mechanical properties of high strength line pipe by thermal coating treatment.," in *Proceedings of OMAE2005 24th International Conference on Offshore Mechanics and Arctic Engineering*, Halkidiki, Greece, 2005.

[10] K. Antoniou, "Numerical simulation of JCO-E line pipe manufacturing and its influence on the mechanical behavior and strength of offshore pipelines," PhD Thesis, Department of Mechanical Engineering, University of Thessaly, Volos, Greece, 2021.

[11] H. Hibbitt, B. Karlsson and P. Sorensen, "ABAQUS: Theory manual, Version 2016," *Dassault Systèmes Simulia Corp, Providence, RI,* 1992.

[12] A. C. Palmer and J. H. Martin, "Buckle propagation in submarine pipelines," *Nature,* vol. 254, no. 5495, pp. 46-48, 1975.

[13] S. A. Karamanos and C. Eleftheriadis, "Collapse of pressurized elastoplastic tubular members under lateral loads," *International Journal of Mechanical Sciences,* vol. 46, no. 1, pp. 35-56, 2004.

[14] DNVGL-OS-F101, *Submarine pipeline systems*, Det Norske Veritas, Oslo, Norway, 2017.