Numerical prediction of material properties and structural response of JCO-E offshore pipes

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Abstract

The present paper presents the application of advanced finite element tools to predict the influence of cold-forming on material properties and collapse resistance of steel JCO-E pipes. Results are obtained for a thick-walled 30-inch-diameter pipe, corresponding to diameter-to-thickness ratio value less than 20. The numerical simulations are supported by experimental tests determining the material properties of steel pipe and steel plate, which are used for forming the JCO-E pipe, and accounts for the influence of heat-treatment on pipe material and its effects on collapse capacity is discussed. The numerical results are also correlated with recent full-scale collapse experiments performed in C-FER, while both experimental data and numerical results are compared with the DNV-ST-F101 standard predictions, and suggestions on the value of fabrication factor are made, considering the material strength recovery due to heat treatment. Finally, the influence of heat treatment on material strength recovery and the collapse capacity is discussed.

1. Introduction

Large diameter and thick-walled line pipes, which are candidates for both deep offshore applications, are mainly manufactured by cold forming and expanding long plates. In this process the plate is deformed significantly in the inelastic range of its material, and a circular configuration (pipe) is obtained from the initial flat configuration (plate) through the following sequential steps: (a) crimping of plate edges, (b) “J” phase, where the forming tool (punch) forms the one side of the plate through a series of consecutive punching steps and the plate obtains a J-shape, (c) “C” phase, where the other side of plate is deformed by the punch in a manner symmetrical to that followed in J phase, (d) “O” phase, where a quasi-round configuration is obtained, (e) welding stage where the plate ends are welded, and (f) expansion phase where a mechanical expander is used to expand the pipe and finally obtain the desired characteristics. These cold-forming steps affect the geometry, such as cross-sectional ovality and wall thickness, and the material properties of the final product [1].

Previous works have reported the effects of cold-forming manufacturing process on the material properties of the finished line pipe, and outlined the reduced collapse capacity of coldformed pipes when compared with the seamless pipes [1]. During the expansion phase of JCO-E, the pipe material is plastically deformed in the circumferential direction, leading to reducing the compressive strength of the pipe material, due to Bauschinger effect. The compressive strength of pipe material is an important factor that controls the structural performance of pipeline under external pressure loading conditions, and thus it is of major concern in offshore applications. However, it is possible to alleviate the material strength degradation with mild heat treatment of the line pipe during the coating cycle of the pipe [2], resulting in higher external pressure capacity.

The present paper continues the authors' research on collapse performance of "heat treated" and "as fabricated" JCO-E pipes [3], focusing on the influence of cold-forming process on the geometric and the material properties of the fabricated pipe. The manufacturing process of a thick-walled 30-inch-diameter line pipe is simulated using a two-dimensional (2D) finite element model. The steel plate thickness is 39 mm. Furthermore, its structural response under external pressure is calculated and compared with the results obtained by a three-dimensional (3D) analysis that simulates the full-scale experiment performed in C-FER [3]. The beneficial effect of heat treatment on the compressive strength of pipe material and on the collapse strength of the pipe is also examined. The numerical predictions of the collapse pressure are also compared with the predictions of DNV-ST-F101 [4] formula. Finally, the variation of mechanical properties through the pipe thickness is discussed and its influence on the external pressure capacity of the pipe is investigated.

2. Numerical modelling

2.1. Description of JCO-E manufacturing process

The JCO-E manufacturing process is simulated using a quasi-two-dimensional (2D) finite element model referred to as "Model 1". In this model, the inelastic response of the steel plate material is described with a user-defined material subroutine (UMAT) which employs a nonlinear kinematic hardening plasticity model developed and implemented by the research team in previous works [5]. The finite element model simulates rigorously the final line pipe product from the initial flat configuration of plate to the series of consecutive mechanical steps, and the final circular configuration of pipe after unloading from the expansion stage. The numerical analysis is performed using ABAQUS/Standard finite element package [6].

The forming parameters for simulating the JCO-E manufacturing process of the 30-inch-diameter line pipe have been provided by Corinth Pipeworks S.A. (CPW). More specifically, geometric parameters, such as the dimensions of the plate, the forming dies, the punch, the expander segments, and kinematic parameters, such as initial positions and displacements of each part, constitute the basic input information for simulating the fabrication process in a realistic manner.

A 3D schematic representation of the JCO-E manufacturing process is shown in Figure 1. The crimping stage is simulated by considering the inner die (upper) fixed and letting the outer die (lower) move upwards, and subsequently bend the plate edges up to a desired deformation level. The stage is completed by drawing back the outer die, causing the plate to unload elastically. Figure 1 presents the J-C-O steps (b, c and d in Figure 1) that follow after crimping step in the numerical analysis. In these steps, the plate is subjected to several punching steps, which are forcing the plate to progressively deform under local bending and unloading conditions across the plate width. The number of punching steps is the same between the two crimped edges (J and C steps). Final punching occurs at the centre of plate width, so that a quasi-circular configuration is obtained after unloading. Followingly, the two plate edges come into contact by applying a mechanical load on their lateral surfaces. The subsequent step of welding is not performed in the current simulation, since the welding process induces small residual stresses in the pipe and therefore, it has negligible effect on the buckling pressure of the pipe, as demonstrated in a previous study [7]. The last step of the manufacturing process is the expansion stage, as shown in Figure 1, where twelve expander segments are displaced outward in the radial direction, expanding the pipe, so that the pipe diameter size is controlled.

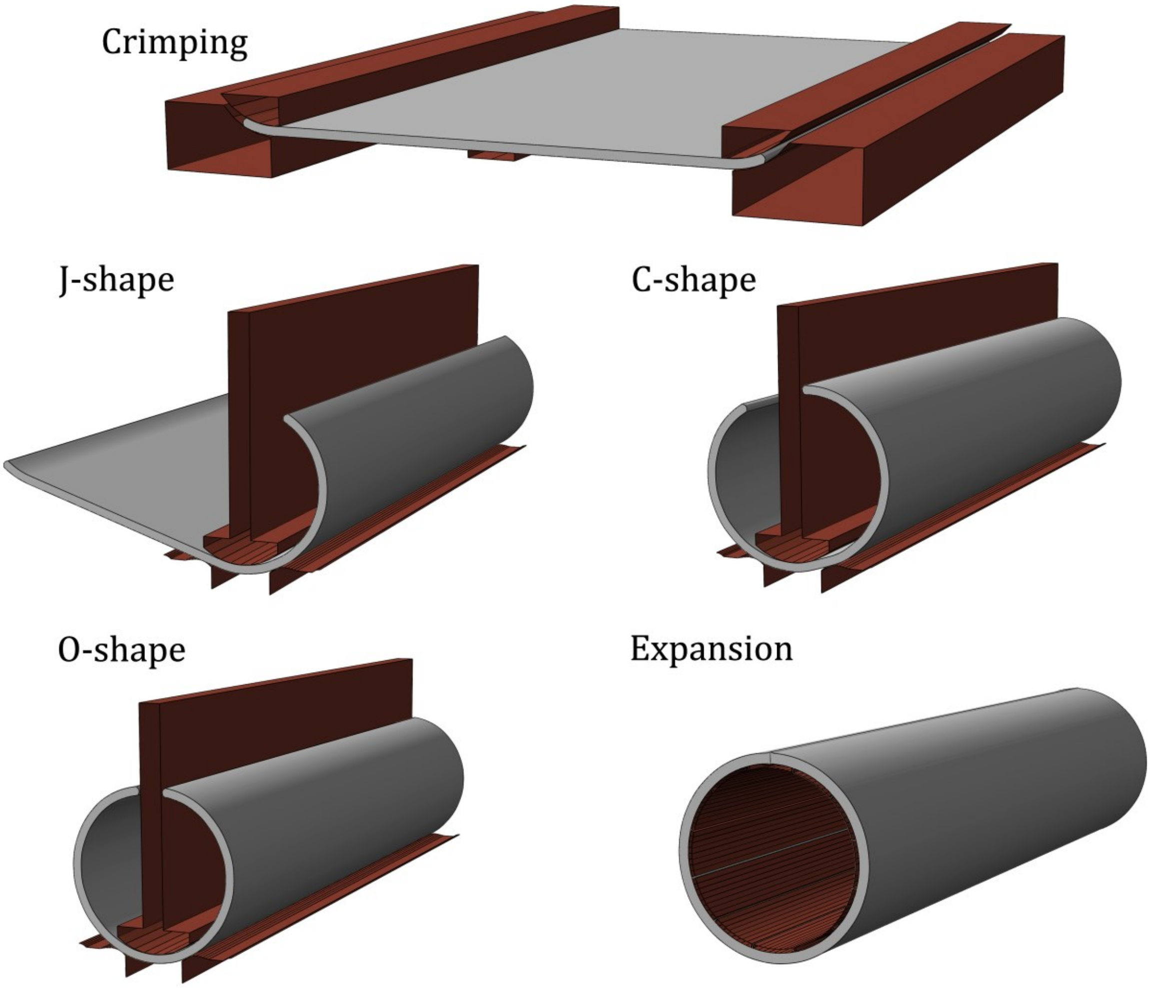

Figure 1. Schematic representation of JCO-E manufacturing process; (a) Crimping, (b) J-phase, (c) C-phase, (d) O-phase, (e) Expansion.

In the 2D finite element analysis of the manufacturing process, the forming tools and dies are modelled as analytical rigid surfaces, whereas four-node reduced integration generalized plane strain continuum elements (denoted as CPEG4R in ABAQUS/Standard) are used in the deformable plate, so that the conditions are similar to those imposed in a real pipe mill, and therefore the out of plane deformation during the process is taken into account. More specifically, twelve elements have been used in the through thickness direction of plate, and the size of elements in the circumferential direction is chosen equal to 16% of thickness. The contact between the plate and the rigid surfaces is modelled using a "master-slave" algorithm with frictionless contact property; in the contact pair the undeformed rigid bodies of dies and tools represent the master surfaces, whereas the deformable plate constitutes the slave surface. Special care is given during the JCO steps to avoid the relative motion between the punch surface and the upper side of plate during punching.

2.2. Material model

The sequence of punching steps across the plate width during the JCO process results in significant plastic deformation of the plate. Each punching step imposes local bending, and therefore the outer and the inner part of the plate wall is deformed under tension and compression, respectively. Furthermore, the expansion step strengthens the pipe material of the outer pipe wall further in tension, making it vulnerable to reverse loading, due to the Bauschinger effect. Since reverse loading conditions exist at the outer part of the pipe wall, when external pressure is uniformly applied on the pipe surface, an appropriate plasticity model should be employed to account for the Bauschinger effect, simulating the material response under reverse or cyclic loading stress paths. Herein, a Von Mises model with plasticity nonlinear kinematic/isotropic hardening is employed, and is described in more detail by Chatzopoulou et al. [5].

A series of experiments, which are representative of the deformation history during the JCO-E manufacturing process, have been carried out to determine the material properties of the X60 steel grade material of the plate and calibrate the plasticity model. The experimental procedure consists of tension-compression-tension loading on specimens extracted from the steel plate at different locations and orientations following the recommendations of SEP 1240 [8]. Figure 2 presents the experimental stress-strain curve of the X60 steel plate material and the corresponding numerical fit from the plasticity model.

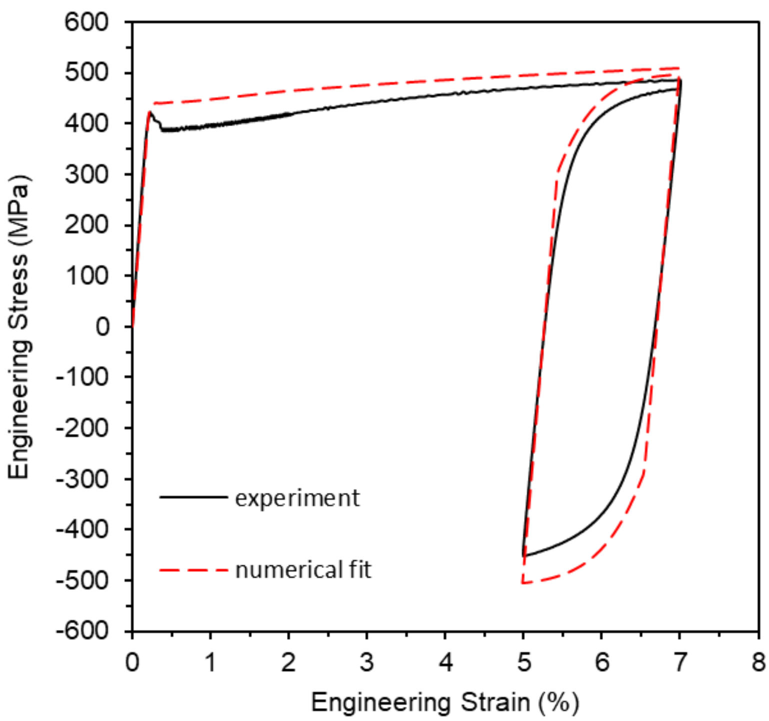

Figure 2. Experimental curve of the X60 steel plate, and the corresponding numerical fit.

3. Numerical results

3.1. Simulation of JCO-E manufacturing process

The deformation configurations of the plate during the manufacturing process are shown in Figure 3 for the initial crimping step and the subsequent “J”, “C” and “O” steps. In the present numerical analysis, fifteen punching steps are applied during the JCO steps. After removal of forming tool (JCO punch), a secondary forming tool referred to as “finishing press” (Figure 4) is used to reduce the gap by imposing two extra bending steps on the two crimped sides of the plate configuration after the O-step, as shown in Figure 4b and Figure 4c. The final gap is depicted in Figure 4d and is significantly lower than the one obtained after the O-step (Figure 4a). The initial gap (Figure 4a) and the final gap (Figure 4d) are in accordance with measurements with actual 30-inch-diameter pipe provided by CPW. At the end of the extra punching step, the final gap (Figure 4d) is closed and the two plate edges are kept in contact, using a “no separation” contact algorithm.

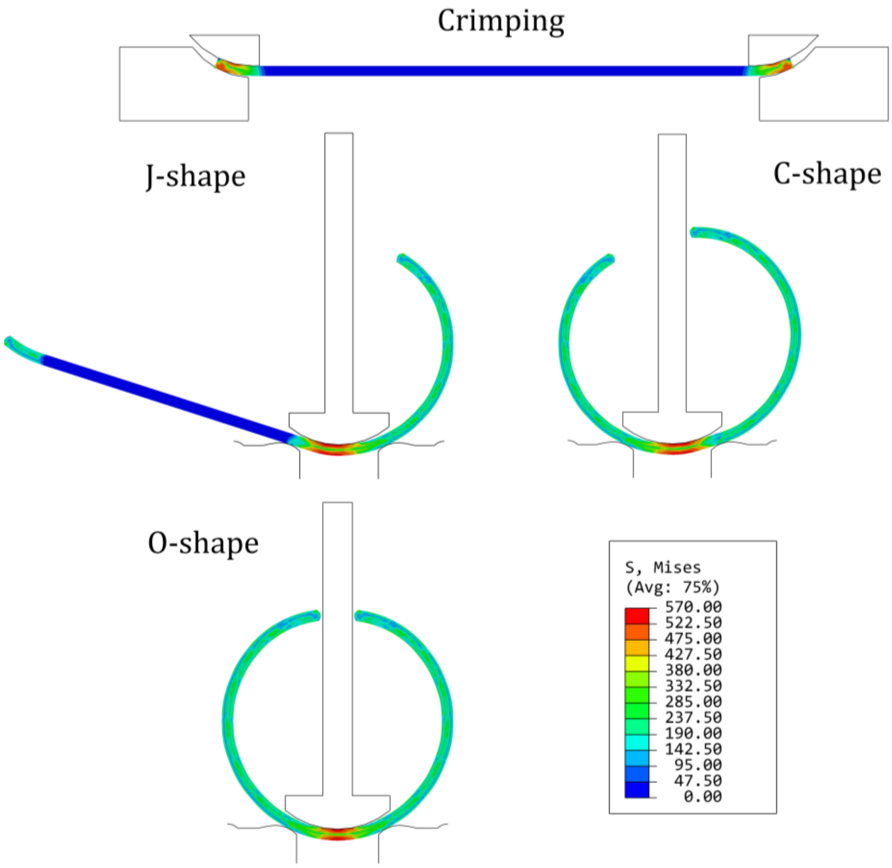

Figure 3. Plate deformation during JCO manufacturing process prior to welding; von Mises contour plot.

The nearly circular pipe configuration obtained after gap closing and welding is referred to as JCO pipe, as shown in Figure 5a. Subsequently, expansion of the JCO pipe is performed, as shown in Figure 5b, using twelve expander segments that move radially outwards. The final configuration of pipe, obtained after removing the expander segments, is referred to as "JCO-E pipe" and corresponds to the final product of the fabrication process, as shown in Figure 5c. The amount of expansion induced in the pipe is quantified in terms of the so-called "expansion strain" (ε_E), expressed by:

$$\varepsilon_E = \frac{C_E - C_W}{C_W} \tag{1}$$

where C_E and C_W are the lengths of pipe circumference after (Figure 5c) and before (Figure 5a), the expansion phase respectively. The expansion strain expression adopted in the present study is also adopted in pervious works [1], [5], [7]. The expansion strain value should be considered as a permanent strain of the final line pipe shape. The expansion strain applied on the JCO pipe of Figure 5, is equal to 1.30%, which is an approximate value of the actual expansion magnitude of the 30-inch-diameter pipe fabricated in the pipe mill. Considering this amount of expansion, the inner diameter of the JCO pipe at 0, 45 and 90-degree locations from the weld seam is 675mm, 675mm and 679mm, respectively, while the corresponding values of the JCO-E pipe are 687mm, 686mm and 686mm. The numerical predictions of the inner diameter of both configurations (JCO and JCO-E) are in very good agreement with actual measurements at the corresponding locations.

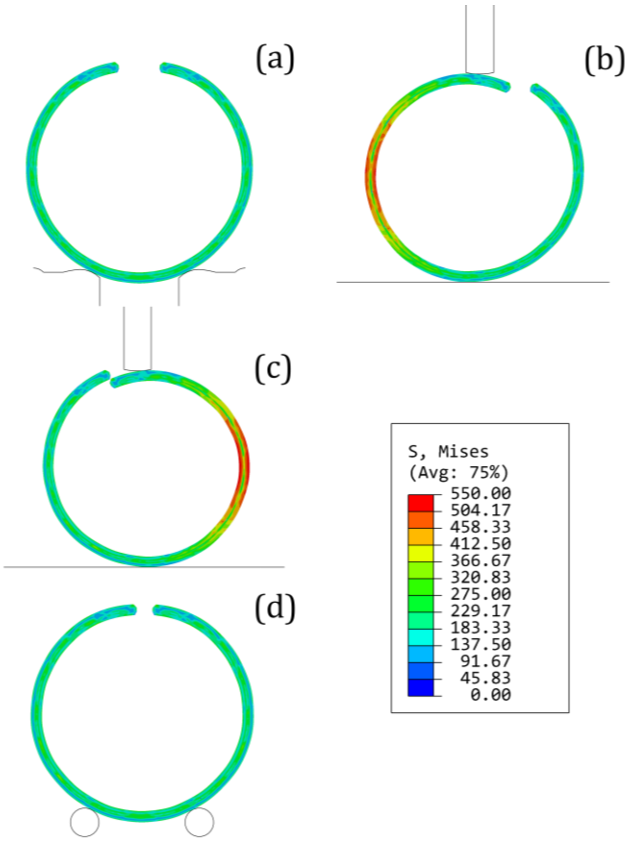

Figure 4. Deformation sequence of JCO pipe under the finishing press; von Mises contour plot.

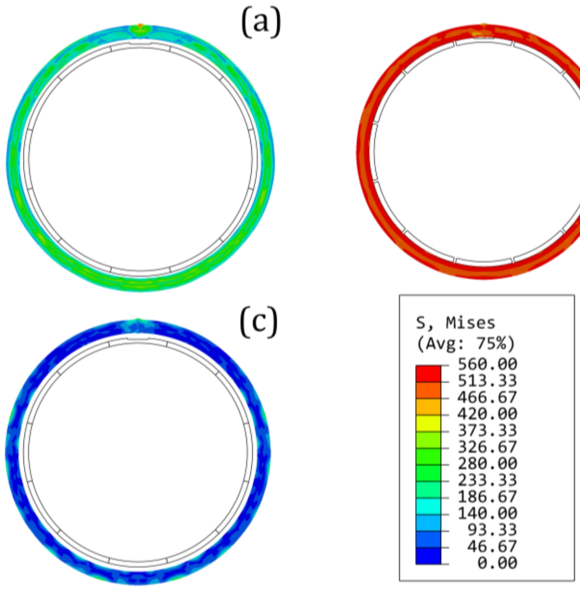

Figure 5. Deformation sequence of expansion phase, resulting in the final pipe geometry of the JCO-E pipe; von Mises contour plot. (a) Before expansion (JCO pipe), (b) at maximum expansion (here ε_E=1.3%), (c) final stage after unloading (JCO-E pipe).

3.2. Effect of expansion on the geometry and, pipe structural integrity in deep water

The finite element model presented in section 2 is capable of simulating rigorously the JCO-E manufacturing process and the structural strength of the pipe under external pressure loading. Following the step of unloading from expansion (JCO-E pipe), uniform external pressure is applied on the outer surface of the pipe. During the pressurization step, the modified Riks' algorithm is employed to capture the maximum pressure at the onset of collapse and trace the post-buckling response.

In JCO-E pipes, the expansion strain ε_E is an important parameter with significant influence on the resistance of pipes under external pressure. The effect of expansion on the collapse pressure (P_{co}) of the JCO-E pipe under consideration is shown in Figure 6, considering a wide range of expansion strain values (ε_E). For small values of ε_E (up to 0.7%), P_{co} is an increasing function ε_E. For ε_E values ranging between 0.7% and 1.8%, the P_{co} value remains nearly constant. It is worth noticing that the maximum collapse pressure is equal to 37.9 MPa at 1.69% expansion strain, whereas at 1.30% strain (an approximate value of the expansion strain used in the pipe mill) the P_{co} value is only 1% lower. Increasing the ε_E value beyond 1.8% the collapse pressure reduces, as shown in Figure 6. This is attributed to the Bauschinger effect, which decreases the circumferential compressive strength. Also note that the maximum allowable expansion strain, according to DNV-ST-F101 standard [4], is 1.50%, which falls within the optimum range of expansion.

The effect of expansion strain on the geometric configuration of line pipe is also investigated. The residual cross-sectional ovality (O_o) of the pipe at the end of the fabrication process is measured, using the following expression:

$$O_o = \frac{D_{max} - D_{min}}{D} \tag{2}$$

where D_{max} and D_{min} are the maximum and minimum values of the outer diameter, and D is the nominal value of the outer diameter. The interaction between the cross-sectional ovality and the applied expansion strain is shown in Figure 6 for the 30-inch-diameter JCO-E pipe under consideration. The results demonstrate that the cross-sectional ovality after the JCO stage before expansion, is approximately equal to 0.6%. Subsequently, increasing the expansion strain, the cross-sectional ovality of the pipe decreases. This reduction is observed up to about 1.3% expansion strain, reaching a value lower than 0.05%, while further increase of expansion strain has negligible effect on the ovality of the JCO-E pipe.

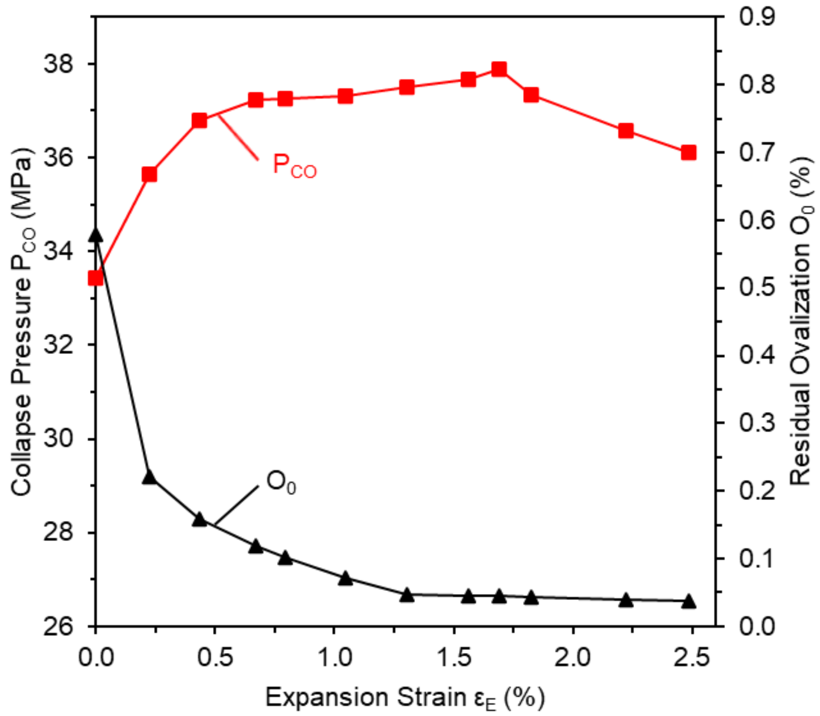

Figure 6 Effect of expansion on residual cross-sectional ovality (O_o) prior to pressurization and the corresponding collapse pressure (P_{co}).

Figure 7 presents the average thickness of the JCO-E pipe under consideration (final product) with respect to different expansion levels and is also compared with the initial thickness of plate (39mm). The numerical results demonstrate that the average wall thickness of the line pipe decreases with increasing expansion strain in a quasi-linear manner, due to "Poisson" effect in the inelastic range of steel material. The results also show that the thickness of the JCO pipe (before expansion) is reduced by 0.1mm with respect to the initial plate thickness, and this is due to local bending induced by the punching steps during the J-C-O phases, as shown in Figure 7 at zero expansion strain.

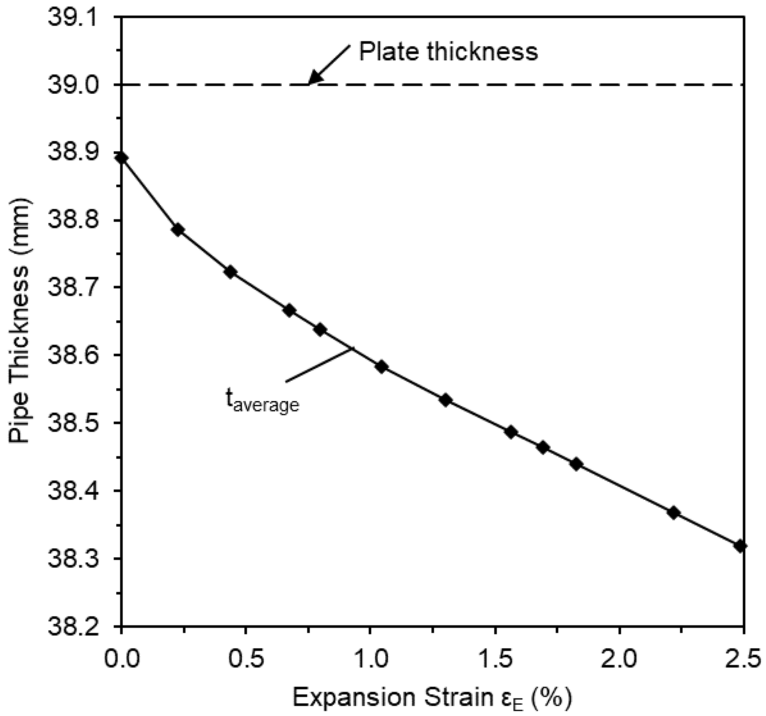

Figure 7 Effect of expansion strain on the average wall thickness of the JCO-E line pipe, compared with the plate thickness.

3.3. Effect of mild heat treatment on pipe collapse capacity

The collapse performance of JCO-E line pipes under external pressure has been studied in a previous work by the authors [3]. In that work, the effects of mild heat treatment on the compressive strength of the line pipe material and on the collapse pressure were examined. This heat-treatment corresponds to a typical coating process of the line pipe. A thermally-treated pipe, manufactured by CPW, with the geometric and material characteristics of the 30-inch JCO-E pipe under consideration was subjected to full-scale collapse test [3]. The collapse test procedure was also numerically simulated, using a three-dimensional (3D) finite element model (Model 2), accounting for the material properties of the as-fabricated (AF) and the heat-treated (HT) conditions.

Material stress-strain curves have been obtained experimentally from uniaxial compression tests on coupon specimens extracted and machined from the outer part of AF and HT pipes in the circumferential direction. The experimental curves at 90, 180 and 270-degree locations around the circumference are averaged, and the corresponding responses are shown in Figure 8. Furthermore, the stress-strain curve of the X60 grade steel (plate material) is shown in Figure 8. The Bauschinger effect, due to reverse loading, is clearly shown in Figure 8 in terms of the reduced proportional limit of the AF and the HT curves, compared with the plate material curve. Additionally, the comparison between the AF and the HT curve demonstrates the beneficial effect of mild heat treatment on material strength (material strength recovery).

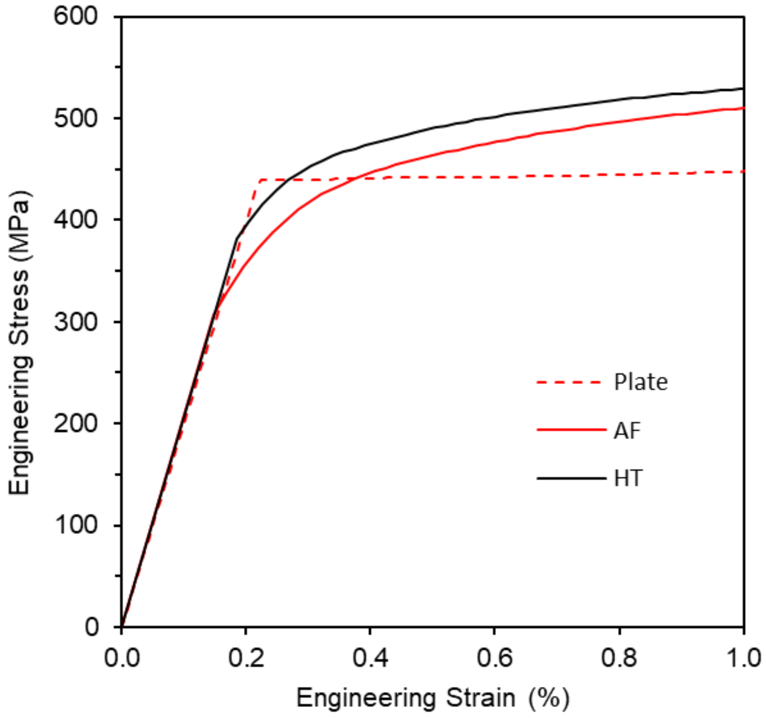

Figure 8 Averaged experimental compressive stress-strain curves at the outer part of pipe before and after the heat treatment, and plate material curve.

The experimental and numerical results on the collapse pressure are summarized in Table 1. The results include the numerical collapse pressure obtained from Model 1 described in Section 2, at 1.30% expansion strain, which is an approximate value of the expansion strain used in the pipe mill. The collapse pressure values obtained from the two numerical models are in good agreement. Furthermore, the numerical prediction of the full-scale collapse pressure is also very successful. Finally, Table 1 shows that the collapse pressure is increased by 13% for the case of the heat-treated pipe, compared with the as-fabricated pipe.

Table 1 Experimental and numerical results of collapse pressure results (in MPa).

Model 2			**Model 1**	**Full-scale test (HT)**
Plate	**AF**	**HT**	**AF**	
44.6	38.5	43.4	37.5	43.4

The collapse capacity of the 30-inch-diameter JCO-E pipe is also quantified using the DNV-ST-F101 design standard [4]. The results are presented in Table 2 for two values of fabrication factor (a_{fab}) namely 0.85 and 1 to account for the as-fabricated (AF) and heat-treated (HT) material properties. The collapse pressure predictions using the specification formula appear to be conservative compared to the experimental and numerical results of Table 1, and this is attributed to the high value of ovality parameter proposed by the standard (0.5%).

Table 2 Collapse pressure predictions (in MPa) using the DNV-ST-F101 [4] collapse formula for the as-fabricated (AF) and heat-treated (HT) conditions.

DNV-ST-F101 formula parameters	$\alpha_{fab} = 0.85$	$\alpha_{fab} = 1$
• AF yield strength: 464 MPa (at 0.5% total strain of AF stress-strain curve in Figure 8) • HT yield strength: 490 MPa (at 0.5% total strain of HT stress-strain curve in Figure 8) • Elastic properties of steel: E=207 GPa, v=0.3 • Diameter: 761.4 mm (average value of outer diameter [3]) • Thickness: 38.29 (averaged value [3]) • Minimum value of ovality proposed by the standard: 0.5 %	35.0	41.4

4. Conclusions

The manufacturing process and the collapse performance of a thick-walled 30-inch-diameter JCO-E pipe (D/t≈20) is investigated, using advanced numerical tools. A two-dimensional (2D) finite element model is used (Model 1), which simulates the manufacturing process of the JCO-E pipe and predicts its collapse pressure. The geometric characteristics of the fabricated pipe predicted by Model 1 are in very good agreement with measurements provided by the pipe mill.

The effects of pipe expansion on its geometric characteristics and on its external pressure capacity are also examined. Increasing the expansion level up to about 0.7%, the cross-sectional ovality of the fabricated pipe is reduced and the corresponding collapse pressure is increased. For expansion strain values between 0.7% and 1.8%, the value of collapse pressure remains nearly constant, whereas for expansion strain values beyond 1.8%, the collapse pressure decreases. The average wall thickness of JCO-E pipe is computed for different values of expansion strain, and the results indicate a quasi-linear dependance of pipe wall thickness on the expansion level.

The collapse pressure calculated from Model 1 compares very well with the collapse pressure from a three-dimensional (3D) model that simulates the full-scale collapse test (Model 2). Using Model 2, the effect of mild heat treatment on the collapse pressure is investigated, considering the stress-strain curve before (AF) and after heat treatment (HT). The results show that P_{co} in the HT pipe is increased by 13%, compared to the AF pipe, verifying the beneficial effect of heat treatment. Collapse pressure predictions obtained from the DNV-ST-F101 collapse formula are compared with the numerical and experimental results. The comparison shows that the DNV-ST-F101 formula provides reasonable yet conservative collapse pressure predictions for the pipe under consideration.

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