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<EFFECT OF OVALITY AND ECCENTRICITY ON COLLAPSE PRESSURE OF SUBSEA PIPELINE>

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ABSTRACT

The objective of this study was to investigate the effect of the ovality and eccentricity on the collapse pressure of a sub-sea pipeline subjected to external pressure. The collapse behavior of the sub-sea pipeline containing initial imperfection was evaluated using elastic–plastic finite element (FE) analyses.

API 5L X65 and API 5L X80 Pipelines with D/t values between 7.5 ~ 60 were adopted to investigate the plastic collapse under hydrostatic pressure. A parametric study was shown that the plastic collapse pressure decreased when either the ratio of diameter to thickness or the ovality increased. It was also shown that the plastic collapse pressure decreased with increasing eccentricity regardless of the pipe diameter.

TABLE OF CONTENTS

Paper

1. INTRODUCTION

Pipeline has been widely used to transfer the fluid products such as gas, oil or steam due to its simple geometry. Offshore pipelines for natural gas transmission may be subjected to dent, gouge and plastic deformation by outside force such as hydrostatic pressure, upheaval buckling, mechanical damage and trawling interference [1~3].

Offshore pipeline owners should evaluate the load carrying capacity on the mechanical damaged pipeline to establish the integrity of pipeline. Offshore pipelines are subjected to a number of loading conditions such as hydrostatic pressure, soil load, buoyant force, and internal pressure as a principal load in addition to windy force, wave force, impact load, thermal stress and vibration. Hoop stress caused by the internal pressure acting on the inside surface of pipeline wall is the primary concern to carry out the structural integrity in onshore pipeline, however, external pressure generated by hydrostatic pressure is the most important parameter governing the unstable collapse behavior of the offshore pipeline [4~9].

There are several industrial codes for design, installation, maintenance and operation the offshore pipelines such as DNV OS F101, ISO 13623, API RP 1111, ASME B31.8, CSA Z662 and BSI 8010. The offshore pipeline having ovality up to 3% of the pipe diameter is permitted to safety operation at the industrial codes or institutes. Global ovality in offshore pipelines is generated at the overbend or sagbend area during pipeline installation on the barge ship. DNV OS F101 code specified the wall thickness fabrication tolerance of 0.15t ~ 0.125t with respect to wall thickness [10]. The thickness eccentricity generated from the thickness variation in the cross-section of the pipe is mainly occurred in seamless pipe. Even though, there are lots of researches on the global ovality and thickness eccentricity on the offshore pipeline, little published numerical results for assessing the pressure response of the global ovality and thickness eccentricity offshore pipeline with variation of the ratio of the diameter to wall thickness.

This research was particularly focused on the plastic collapse behavior of the global ovalized pipeline and the thickness eccentricity pipeline. The plastic collapse behavior of the offshore pipelines subjected to hydrostatic pressure was evaluated with the ovality and the thickness eccentricity in finite element analyses.

2. FINITE ELEMENT ANALYSES

2.1 FE Model

The general purpose finite element program, ABAQUS Ver. 6.10, was employed to investigate the influence of initial imperfections on the collapse resistance [11]. API 5L X65 pipe and API 5L X80 with a diameter between 18 *inch* (457 *mm*) to 36 *inch* (914 *mm*) at an interval of 6 *inch* were evaluated to investigate the influence of the diameter [12]. Ratios of diameter to thickness (*D/t*) with 7.5, 15, 30 and 60 were used to finite element analyses.

Two dimensional model for pipe was generated due to geometric, loading symmetries and efficient computation. Mesh convergence studies were performed to obtain adequately refined finite element sizes. The refined meshes with 6 elements through the thickness and 60 elements in circumferential direction were assigned by a CPE4R (A 4-node bilinear plane strain quadrilateral, reduced integration, hourglass control) shell element on the whole of the pipe.

Round bar tensile specimens with reduced sections of 6 *mm* were extracted from the API 5L X65 pipe and API 5L X80, with the tensile curves given in Figure 1. The true fracture strength and the true fracture strain were used in the FE analyses to simulate the failure behavior of the pipe during the denting and pressurizing processes.

2.2 Ovality and eccentricity procedures

Introducing the global ovality into the pipe was achieved by the following procedures. The bottom line of the pipe was fully fixed to prevent a body movement during the introduction of global ovality. The top line of the pipe, with a free boundary condition in the vertical direction was moved down to a pre-determined depth by displacement control. The ovality was calculated from Eq. 1 and Figure 2.

$$f = \frac{D_{\max} - D_{\min}}{D} \tag{1}$$

Where D is the nominal outside diameter, D_{max} is the greatest measured outer diameter of the pipe and D_{min} is the smallest measured outer diameter of the pipe [3, 10].

A center point of the internal diameter was offset with a distance “d” to make a wall thickness eccentricity after the outside perimeter of the pipe was drawn with respect to its outside diameter. The thickness eccentricity, Δ, was calculated from Eq. 2 and Figure 2.

$$\Delta = \frac{t_{\max} - t_{\min}}{t_{nom.}} \tag{2}$$

Where $t_{nom.}$ is the nominal wall thickness, t_{max} is the greatest measured thickness and t_{min} is the smallest measured thickness [3, 10].

Hydrostatic pressure was applied onto the outer surface of the pipe as a distributed load to generate plastic collapse on the globally oval pipe by using the Riks option in ABAQUS [13]. The finite element analysis procedure for the plastic collapse of an offshore pipeline with an initial imperfection is as follows:

(1) The offshore pipeline was modeled using the symmetry boundary condition and the CPE4R shell element.

(2) The external pressure was applied as a distributed load onto the outer surface of the pipe to generate the plastic collapse on the ovality pipe or the thickness eccentricity pipe by using the Riks option of the step module in ABAQUS. Table 1 shows the cases of the FE analyses performed for the pipelines with ovality and thickness eccentricity.

3. RESULT AND DISCUSSION

3.1 FE analyses *vs*. industrial code

The characteristic collapse pressures (P_c) on the pipelines with global ovality under no internal pressure are calculated from DNV OS F101 and FE analyses which are presented in Figure 3. The characteristic collapse pressure for global ovality pipeline in DNV OS F101 is calculated from Eqs. 3 ~ 5.

$$\left(P_c - P_{el}\right)\left(P_c^2 - P_p^2\right) = P_c P_{el} P_p f \frac{D}{t} \quad (3)$$

$$P_{el} = \frac{2E\left(t/D\right)^3}{1-\nu^2} \quad (4)$$

$$P_p = f_y \alpha_{fab} \frac{2t}{D} \quad (5)$$

where P_c is the characteristic collapse pressure, P_{el} is the elastic collapse pressure, P_p is the collapse pressure, f_y is the yield stress to be used in design, E is the elastic modulus, α_{fab} is the fabrication factor (1, 0.93, or 0.85), t is the wall thickness of the pipe, and v is the Poisson's ratio.

The collapse pressure of DNV OS F101 shows slightly lower than that of FE analysis results. It comes from using the yield stress of 464 *MPa* obtained from tensile test on the API 5L X65 pipe but the yield stress of 448 *MPa* and the fabrication factor of 0.85 are employed to calculate Eq. 4 and Eq. 5.

3.2 Effect of the *D/t* on collapse pressure

Figures 4~5 show the collapse pressure on the pipeline having outer diameter of the 18, 24, 30 and 42 *inch* with global ovality on the API 5L X65 and API 5L X80. The collapse pressure is decreased as increasing ovality under the identical outer diameter in addition to the collapse pressure is decreased as the ratio of outer diameter to wall thickness is increased.

In case of *D/t* =7.5, the collapse pressure is linearly decreased as increasing ovality up to 20%, however, the variation in collapse pressure is not large in case of *D/t* =30 or 60. The collapse pressure is considerably influenced by the ratio of the outer diameter to the wall thickness under the identical ovality condition. The collapse pressure under the identical ratio of the outer diameter to the wall thickness shows a same value regardless of the outer diameter and the collapse pressure is decreased as increasing ovality. Reducing rate on the collapse pressure is decreased as increasing ovality and the ratio of the outer diameter to the wall thickness.

Figure 6 illustrates the collapse pressure on the pipeline having the ratio of the diameter to wall thickness of the 7.5, 15, 30 and 60 with global ovality on the API 5L X65 and API 5L X80. The collapse pressure is decreased as increasing ovality under the identical ratio of outer diameter to wall thickness. In case of *D/t*=7.5 and 15, the collapse pressures of the API 5L X80 are higher than that of the API 5L X65, however, the collapse pressures at the pipe with *D/t*=30 and 60 show the nearly identical values regardless of the grade of the pipe.

3.3 Effect of residual stress on collapse pressure

Figure 7 presents the residual stress generated at the pipeline of the having the ratio of the diameter to wall thickness of the 7.5, 15, 30 and 60 after making the global ovality of 8 or 12% into the API 5L X65 pipe. The residual stress is increased as decreasing the ratio of the diameter to wall thickness or increasing the ovality. The residual stress of the pipe having the ovality of up to 12% is less than yield stress of the API 5L X65 pipe.

Figure 8 indicates the collapse pressure on the API 5L X65 pipe having the global ovality of 8 or 12% with the residual stress or without residual stress. The collapse pressure of the pipe with residual stress shows a similar value compared to without residual stress regardless of the ovality. This indicates that the residual stress less than the yield tress of the material does not affect on the collapse pressure.

3.4 Effect of thickness eccentricity on collapse pressure

Figures 9~10 show the collapse pressure on the pipeline having outer diameter of the 18, 24, 30 and 42 *inch* with the thickness eccentricity on the API 5L X65 and API 5L X80. The collapse pressure is decreased as increasing thickness eccentricity under the identical outer diameter in addition to the collapse pressure is decreased as the ratio of outer diameter to wall thickness is increased.

In case of *D/t* =7.5 and 15, the collapse pressure is slightly decreased as increasing ovality up to 16%, however, the variation in collapse pressure is not large in case of *D/t* =30 or 60. The collapse pressure is seriously affected by the ratio of the outer diameter to the wall thickness under the identical thickness eccentricity condition. Reducing rate on the collapse pressure is decreased as increasing the ratio of the outer diameter to the wall thickness.

4. SUMMARY

The present paper provides a plastic collapse behavior of the offshore pipelines with ovality or thickness eccentricity subjected to hydrostatic pressure. Detailed elastic-plastic finite element analyses were performed to estimate the collapse pressure with several of the ovality size, thickness eccentricity and ratio of outer diameter to wall thickness.

A parametric study was shown that the plastic collapse pressure decreased when either the ratio of diameter to thickness or the ovality increased. It was also shown that the plastic collapse pressure decreased with increasing thickness eccentricity regardless of the pipe diameter. It was thought that the collapse pressure of the pipeline having a global ovality was not affected by the residual stress.

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List of Tables

List of Figures

Table 1 Parameters for ovality and thickness eccentricity used in FE analyses.

OD (*mm*)	D/t (nominal thickness)	Ovality %				Thickness eccentricity (%)			
		4	8	12	16	4	8	12	16
		Target dent depth (*mm*)				Nominal thickness – (max. or min. thickness)			
18” (457)	7.5 (60.93)	13.41	26.81	40.22	53.62	2.44	4.87	7.31	9.75
	15 (30.47)	15.84	31.69	47.53	63.37	1.22	2.44	3.66	4.87
	30 (15.23)	17.06	34.12	51.18	68.25	0.61	1.22	1.83	2.44
	60 (7.62)	17.67	35.34	53.01	70.68	0.30	0.61	0.91	1.22
24” (610)	7.5 (81.33)	17.9	35.8	53.7	71.6	3.25	6.51	9.76	13.01
	15 (40.67)	21.1	42.3	63.4	84.6	1.63	3.25	4.88	6.51
	30 (20.33)	22.8	45.5	68.3	91.1	0.81	1.63	2.44	3.25
	60 (10.17)	23.6	47.2	70.8	94.3	0.41	0.81	1.22	1.63
30” (762)	7.5 (101.6)	22.4	44.7	67.1	89.4	4.06	8.13	12.19	16.26
	15 (50.80)	26.4	52.8	79.2	105.7	2.03	4.06	6.10	8.13
	30 (25.40)	28.4	56.9	85.3	113.8	1.02	2.03	3.05	4.06
	60 (12.70)	29.5	58.9	88.4	117.9	0.51	1.02	1.52	2.03
36” (914)	7.5 (121.8)	26.8	53.6	80.4	107.2	4.87	9.75	14.62	19.5
	15 (60.93)	31.7	63.4	95.1	126.7	2.44	4.87	7.31	9.75
	30 (30.47)	34.1	98.2	102.4	136.5	1.22	2.44	3.66	4.87
	60 (15.23)	35.3	70.7	106	141.4	0.61	1.22	1.83	2.44

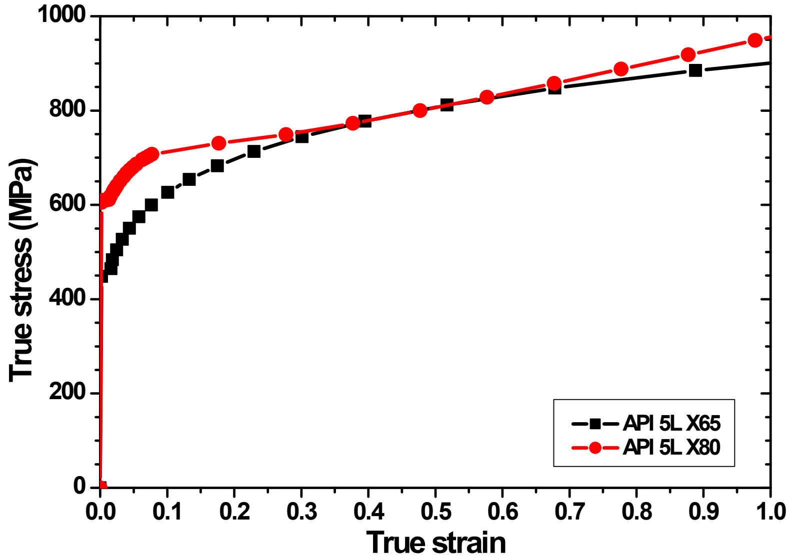

Figure 1. True tensile stress-strain curve for API 5L X65 pipe and API 5L X80 pipe.

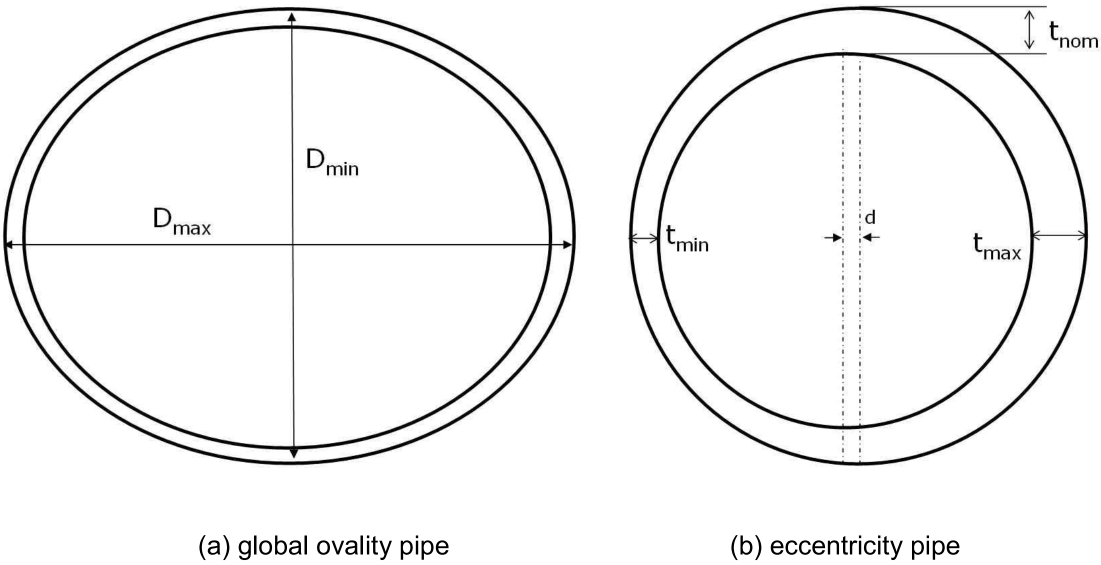

Figure 2. Cross-sectional view of (a) global ovality pipe and (b) eccentricity pipe.

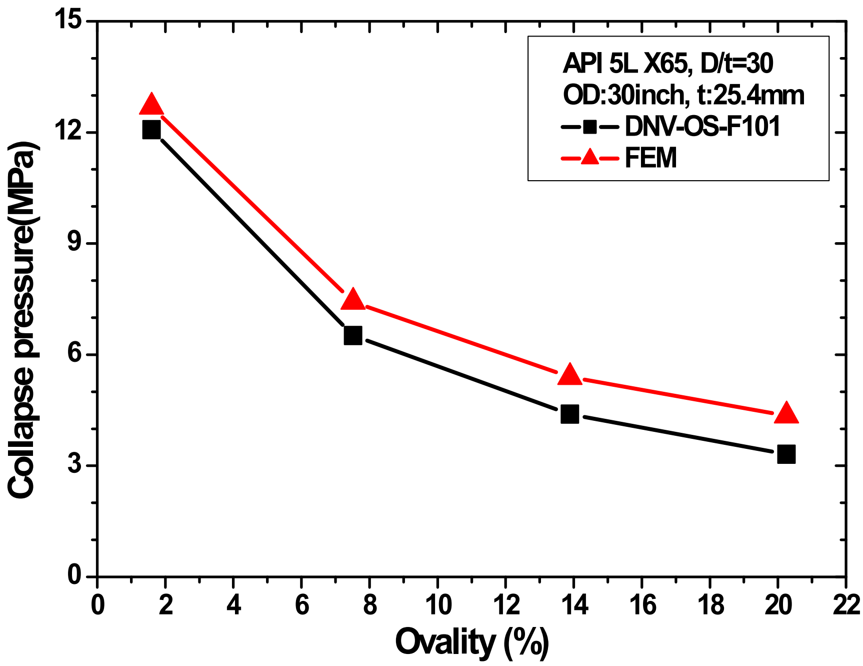

Figure 3. Comparison of the collapse pressure between DNV OS F101 code and FE analyses.

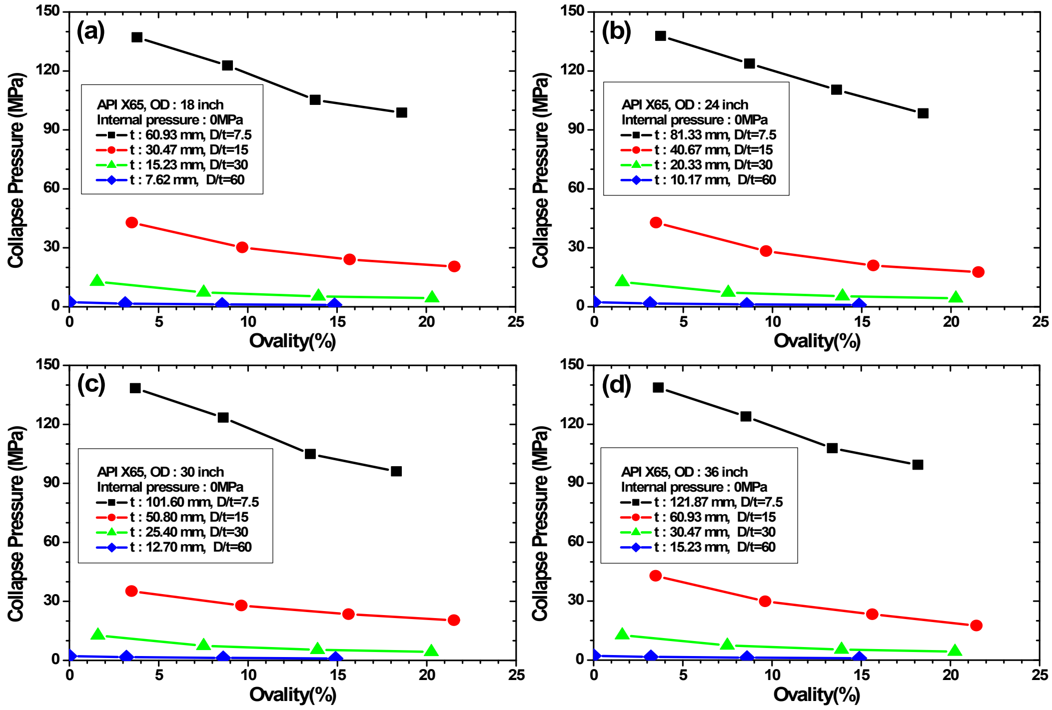

Figure 4. Collapse pressure with variation of *D/t* for API X65 with ovality.

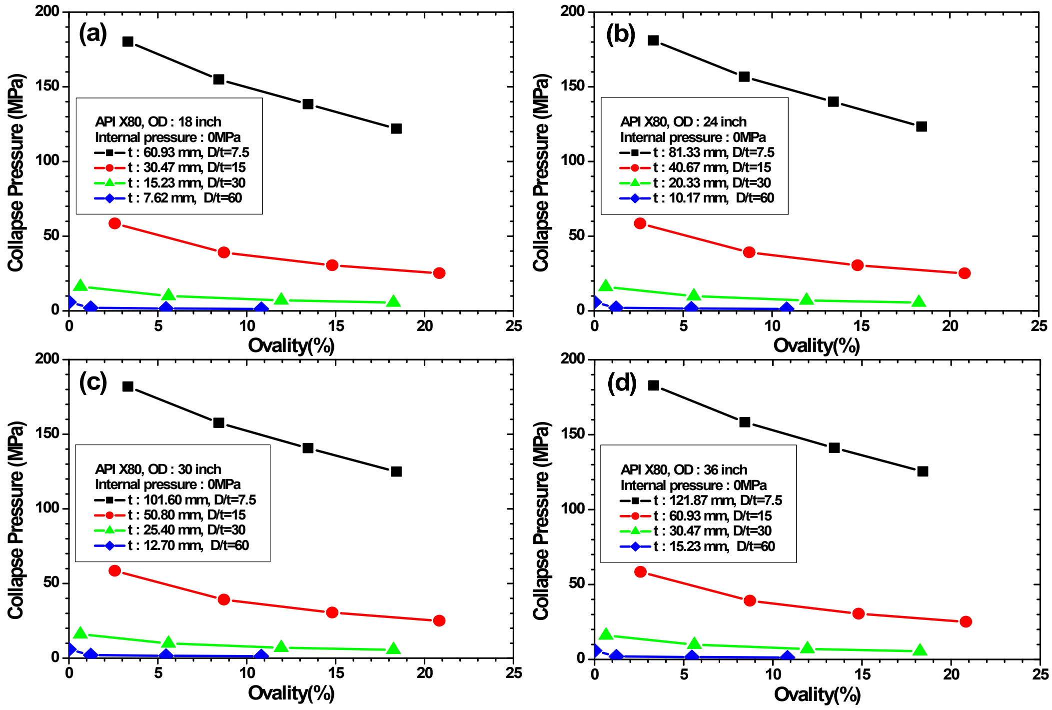

Figure 5. Collapse pressure with variation of *D/t* for API X80 with ovality.

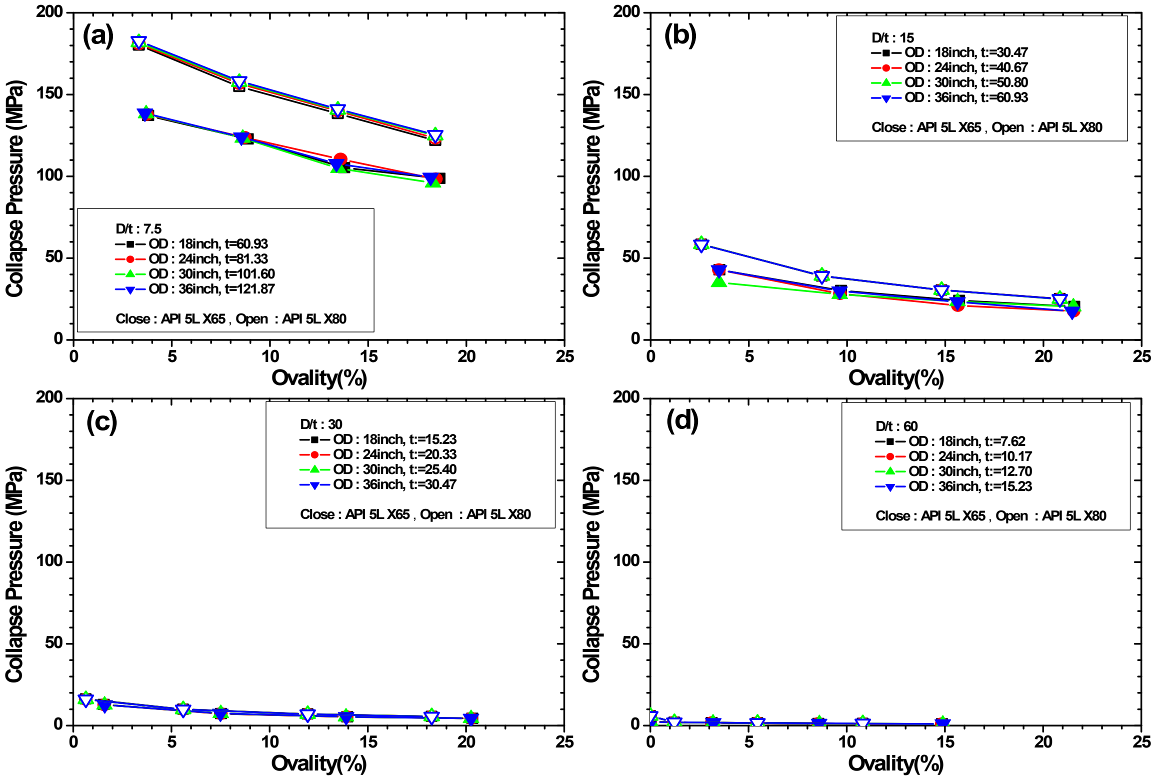

Figure 6. Collapse pressure with variation of pipe diameter for API X65 and API X80 with ovality.

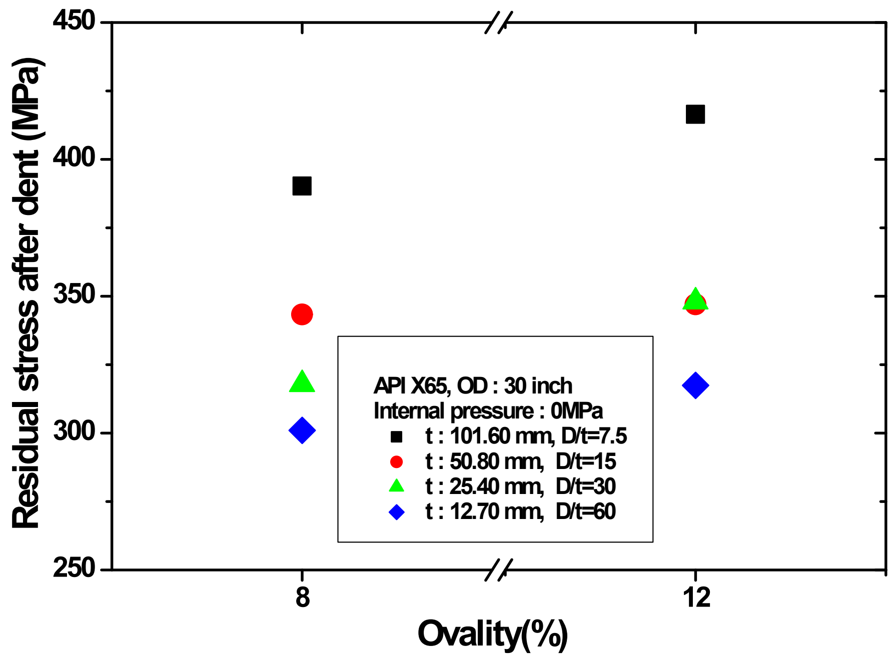

Figure 7. Residual stress after dent with variation of *D/t* for API 5L X65.

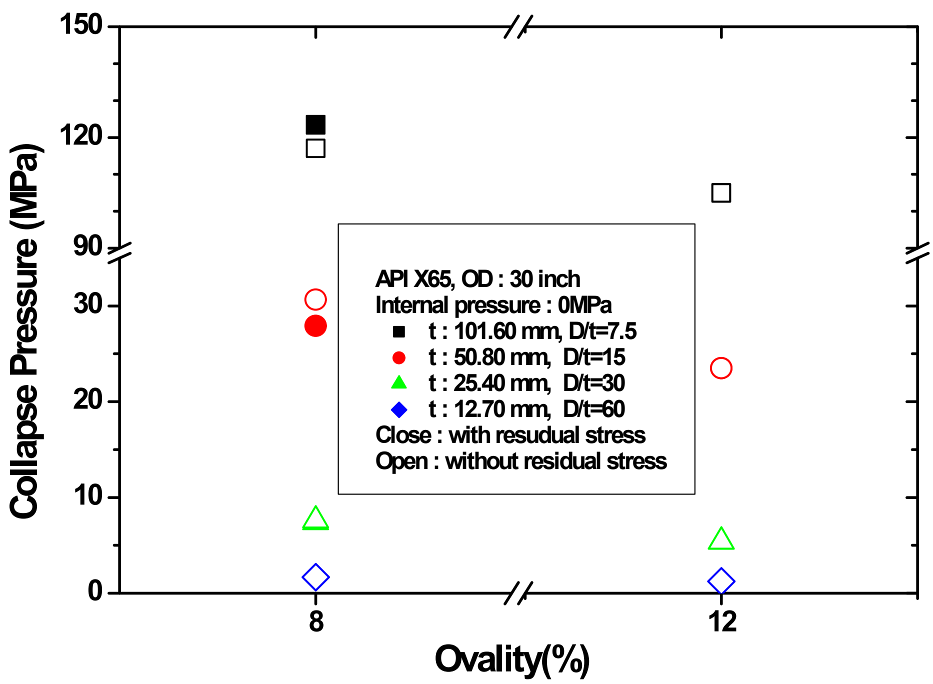

Figure 8. Effect of residual stress on collapse pressure for API 5L X65.

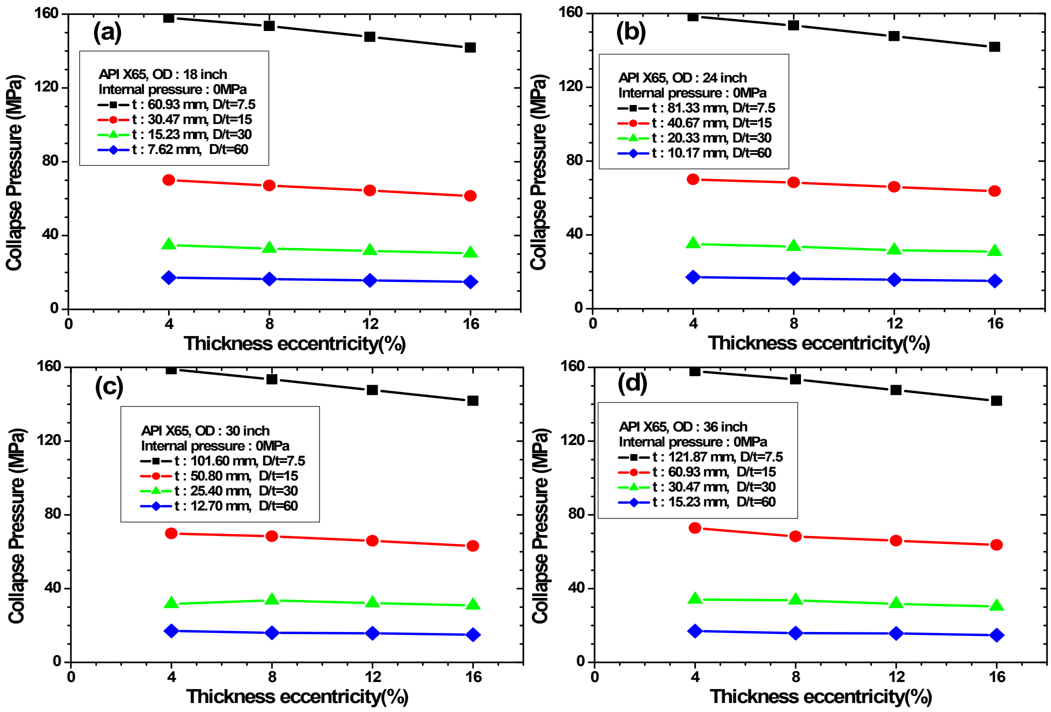

Figure 9. Collapse pressure of the API 5L X65 with thickness eccentricity.

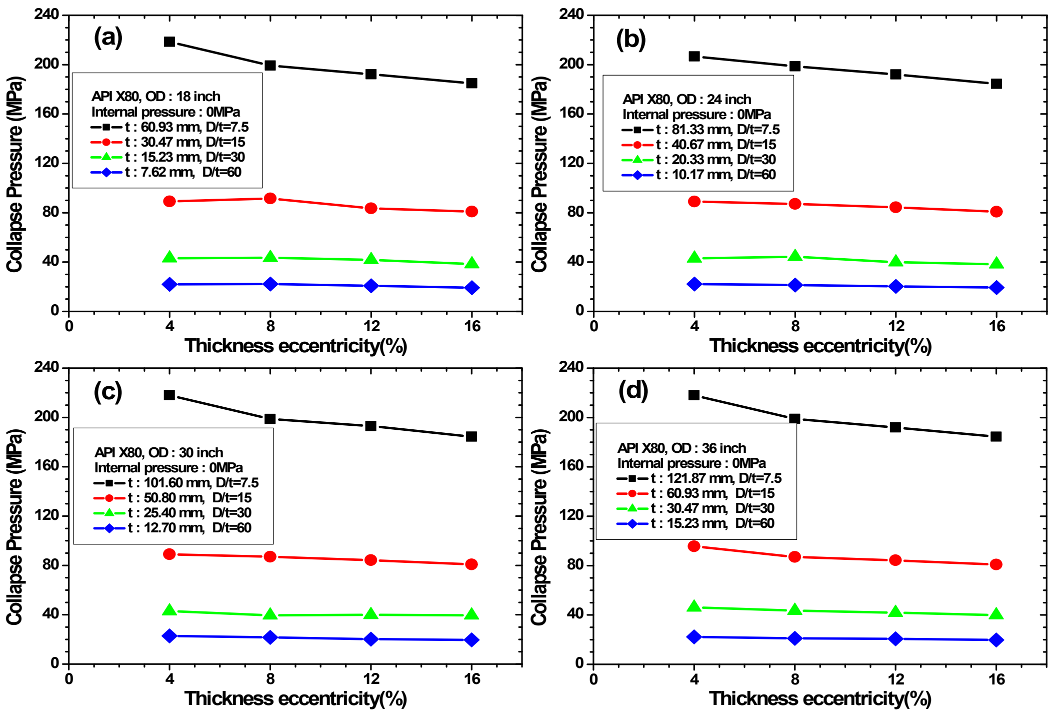

Figure 10. Collapse pressure of the API 5L X80 with thickness eccentricity.