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Mechanical Design of Deepwater Pipeline Wall Thickness Using the Recent Rules

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최신 설계규정에 의한 심해 해저관로 두께의 기계적 설계

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Abstract: *This paper presents a mechanical design of the deepwater pipeline wall thickness using the recent design rules. Characteristics and limitations of the new codes were identified through a case study design in the Gulf of Mexico. In addition to the ASME, API, and DNV codes, the code of federal regulations (CFR) was also utilized in the design. It was found that conservatism still exists within the collapse prediction for water depth greater than 1500m. Comparision of the results from DNV and API codes were presented.*

1. Introduction

This paper presents a mechanical design of the deepwater pipeline wall thickness using the recent design rules. The ollowing design rules were used to determine the wall hickness of a pipeline: API, 1999; ASME, 1999; CFR, 2001 and DNV, 2000. For deepwater pipelines, the determination of the wall thickness is also limited by the installation method in addition to the design rules. This fact was also described in the following papers: Choi, 1998; Choi, 1999; Kopp and Peek, 2001 and Bai, 2001. Wall thickness design was demonstrated using a recent case study in the Gulf of Mexico. The export oil pipeline starts as a 14-inch steel catenary riser (SCR) from a floating platform at the water depth of 1740 m and ends with an 18-inch export pipeline at the shallow water platform at water depth of 85m as shown in Fig. 1. Pipeline data are also presented in Table 1. The pipe properties satisfy the following requirements:

- Allowable hoop stress
- Pressure containment (Burst design)
- Collapse only
- Combined load of bending and external pressure

Pipeline wall thickness design was finalized by an iterative application of the above design requirements.

The design result summarized in Table 1 includes the effect of the installation by a reel-lay method. Reeling and unreeling operation yields a large ovality in the pipe sections.

Corrosion allowances of wall thickness depend on carrying fluid components, oil temperature distribution, and design life of the pipeline. The 14-inch SCR carries very hot oil from platform but the oil temperature cools down quickly and reaches almost ambient temperature at the beginning of the 18-inch pipeline. A corrosion allowance of 1.6 mm for

Table 1 Pipeline data

Pipe Number	OD (inch)	WT (inch)	Reel-lay Ovality (%)	Corrosion Allowance (mm)	Water Depth (m)
P1	18	0.875	2.88	0.28	85-945
P2	18	0.938	2.58	0.28	945-1160
P3	18	1.000	2.33	0.28	1160-1370
P4	18	1.125	1.96	0.28	1370-1580
P5	14	0.875	1.54	1.60	1580-1740
P6	14SCR	0.875	1.54	1.60	1740

Design pressure = 3600 psig
Pipe grade = X-60 for 18″ pipe and X-65 for 14″ pipe
Design life = 20 years for 18″ pipe and 40 years for 14″pipe

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the 14-inch pipeline and 0.28 mm for the 18-inch pipeline were obtained from the other study (hydraulic and corrosion analysis). The pipe ovalities in Table 1 were obtained from the reeling analysis. The sensibility analysis of the pipe ovality was carried out with the DNV code for the local buckling (collapse).

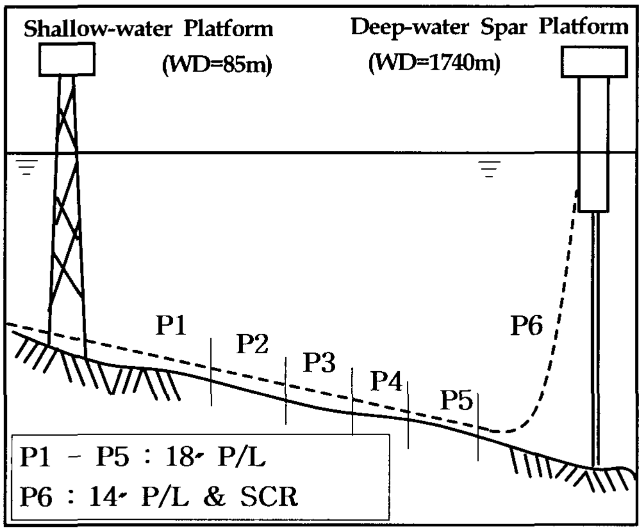

Fig. 1 Sketch of an oil pipeline system

2. Allowable Hoop Stress

2.1 Internal Pressure

The wall thickness of the pipe in Table 1 meet the requirements in accordance with 49 CFR part 195 (CFR, 2001) and ASME B31.4 (ASME, 1999).

The minimum wall thickness for the design pressure of the 18-inch API 5L X-60 pipe is 0.75-inch and satisfies the above criteria excluding corrosion allowance. The internal pressure design is presented in Table 2. Calculated pressures exceed the internal design pressure during the pipeline operation.

Table 2 Internal pressure

Pipe Number	Corrosion Allowance (mm)	Design Pressure (psig)	Calculated Pressure (psig)
P1	0.28	3600	4147
P2	0.28	3600	4449
P3	0.28	3600	4747
P4	0.28	3600	5347
P5	1.60	3600	5429
P6	1.60	3600	4524

Design factors : 0.72 for pipeline and 0.6 for SCR

2.2 Hydrotest Pressure

The hydrotest pressure shown in Table 3 is 125% of the design pressure. The maximum allowable stress by CFR part 250 is 95% of the specified minimum yield strength (SMYS) of the pipe. All the wall thicknesses in Table 1 satisfy the allowable stress limit during the hydrotest.

Table 3 Hydrotest pressure

Pipe Number	Hydrotest Pressure (psig)	Calculated Stress (ksi)	Calculated Stress (% SMYS)
P1	4500	46.3	77.1
P2	4500	43.2	72.0
P3	4500	40.5	67.5
P4	4500	36.0	60.0
P5	4500	36.0	55.4
P6	4500	36.0	55.4

3. Pressure Containment (burst)

3.1 Burst Design by API RP1111

The hydrostatic test pressure, the pipeline design pressure, and the incidental overpressure, including both internal and external pressures acting on the pipelines, shall not exceed that determined by the formulae (API, 1999):

$$p_t \leq f_d f_e f_t p_b \tag{1a}$$

$$p_d \leq 0.80\, p_t \tag{1b}$$

$$p_a \leq 0.90\, p_t \tag{1c}$$

where,

f_d = internal pressure (burst) design factor

f_e = weld joint factor

f_t = temperature derating factor

p_a = incidental overpressure

p_b = specified minimum burst pressure of pipe

p_d = pipeline design pressure

p_t = hydrostatic test pressure

The specified minimum burst pressure (p_b) is determined by the following formulae:

$$p_b = 0.45(S+U)\ln\left(\frac{D}{D_i}\right) \tag{2}$$

where,

D = outside diameter of pipe

D_i = $D-2t$ = inside diameter of pipe

S = specified minimum yield strength of pipe

t = nominal wall thickness of pipe

U = specified minimum ultimate tensile strength of pipe

The pipeline meets the requirements in accordance with API RP1111. Results of the calculations are shown in Table 4. Required wall thicknesses, including the corrosion allowance, by the burst design of API RP1111 are below the design wall thickness.

3.2 Burst Design by DNV OS-F101

The selection of the limit states and related partial safety factors and safety classes are very important for the wall thickness design (DNV, 2000, 2001). Burst design belong to the ultimate limit state (ULS).

The pressure containment shall fulfill the following criteria:

$$p_{li} - p_o \le \frac{p_b(t_1)}{\gamma_{sc} \cdot \gamma_m} \tag{3}$$

where,

$t_1 = t - t_{fab} - t_{corr}$

t_{fab} = fabrication allowance of wall thickness

t_{corr} = corrosion allowance of wall thickness

$p_{li} = p_d \cdot \gamma_{inc} + \rho_{cont} \cdot gh$ = local incidental pressure

γ_{inc} = ratio between incidental and design pressure

ρ_{cont} = density of the content of pipeline

g = acceleration due to gravity

h = height difference between the point and the reference point

p_o = external pressure

γ_{sc} = safety class resistance factor

γ_m = material resistance factor

The pressure containment resistance, $p_b(t_1)$ is given by:

$$p_b(t_1) = Min(p_{b,s}(t_1);\ p_{b,u}(t_1)) \tag{4}$$

Yielding limit state:

$$p_{b,s}(t_1) = \frac{2 \cdot t_1}{D - t_1} \cdot f_y \cdot \frac{2}{\sqrt{3}} \tag{5}$$

Bursting limit state:

$$p_{b,u}(t_1) = \frac{2 \cdot t_1}{D - t_1} \cdot \frac{f_u}{1.15} \cdot \frac{2}{\sqrt{3}} \tag{6}$$

Characteristic yield strength:

$f_y = (S - f_{y,temp}) \cdot \alpha_u$

Characteristic tensile strength:

$f_u = (U - f_{u,temp}) \cdot \alpha_u \cdot \alpha_A$

where,

$f_{y,temp}$ = derating of yield strength due to temperature

$f_{u,temp}$ = derating of tensile strength due to temperature

α_u = material strength factor

α_A = anisotropy factor

The pipelines meet the requirements in accordance with DNV OS-F101. Results of the calculations are shown in Table 4. Burst design by DNV OS-F101 yields more conservative wall thicknesses than those of the API RP1111. However, the required wall thicknesses by the DNV code are still below the designed wall thicknesses including the corrosion allowance. Therefore the selected wall thicknesses in Table 1 satisfy the burst design requirement of both DNV and API codes.

Table 4 Burst design

Pipe Number	API RP1111		DNV OS-F101	
	Burst pres. (psig)	Required WT (in)	Burst Pres. (psig)	Required WT (in)
P1	6126	0.722	5821	0.792
P2	6597	0.722	6266	0.792
P3	7064	0.722	6707	0.792
P4	8015	0.722	7605	0.792
P5	7869	0.590	7452	0.700
P6	7869	0.691	7452	0.781

4. Pipeline Collapse

4.1 Collapse Design by API RP1111

During construction and operation, oil pipelines may be subjected to meet conditions where the external pressure exceeds the internal pressure. The differential pressure acting on the pipe wall due to hydrostatic head can cause collapse of the pipe.

The collapse pressure of the pipe must exceed the net external pressure everywhere along the pipelines as follows:

$$(p_o - p_i) \le f_c p_c \tag{7}$$

where,

f_c = collapse factor

p_i = internal pressure

p_c = collapse pressure of the pipe

The following equations can be used to approximate collapse pressure:

$$p_c = \frac{p_y p_e}{\sqrt{p_y^2 + p_e^2}} \tag{8a}$$

$$p_y = 2S\left(\frac{t}{D}\right) \tag{8b}$$

$$p_e = 2E\frac{\left(\frac{t}{D}\right)^3}{(1-\nu^2)} \tag{8c}$$

where,

E = modulus of elasticity

p_e = elastic collapse pressure of pipe

p_y = yield pressure at collapse

ν = Poisson's ratio (0.3 for steel)

The collapse formula in API RP1111 does not consider the ovality of the pipe. The allowable ovalities during the pipe manufacturing are specified in the API 5L specification (API, 2000). The selected wall thicknesses in Table 1 satisfy the requirements in accordance with API RP1111. Results of calculations are shown in Table 5. The calculated collapse water depths due to the external pressure are deeper than the maximum design water depth along the pipeline.

4.2 Collapse Design by DNV OS-F101

The characteristic resistance for collapse pressure (p_c) shall be calculated as:

$$(p_c - p_e) \cdot (p_c^2 - p_p^2) = p_c p_e p_p f_o \frac{D}{t_2} \tag{9}$$

where,

$p_p = 2 \cdot f_y \cdot \alpha_{fab} \cdot \frac{t_2}{D}$ = plastic collapse pressure

α_{fab} = maximum fabrication factor

$f_o = \frac{D_{\max} - D_{\min}}{D}$ = DNV ovality

$t_2 = t - t_{corr}$

The external pressure at any point along the pipeline shall meet the following criterion (system collapse check):

$$p_o \leq \frac{p_c}{1.1 \cdot \gamma_m \cdot \gamma_{sc}} \tag{10}$$

Table 5 shows the comparison of API and DNV codes. DNV code results less water depths than those of the API. It means that the wall thickness required by DNV collapse criteria are thicker than those required by API code.

Fig. 2 shows the sensitivity of the ovality on collapse buckling. Ovality of 0.75% is the limit manufactured by API 5L specification (API, 2000). Ovality of 1.44% corresponds to the typical steep s-lay method. Ovality of 2.88% corresponds to the reel-lay and was used for the determination of the wall thickness in Table 1. The pipeline meets the requirement in accordance with DNV OS-F101. Calculated collapse water depths during the operation are shown in Fig. 3.

Table 5 Comparison of collapse water depths

Pipe Number	Maximum Design Depth (m)	Collapse Water Depth (m)	
		API RP 1111 (m)	DNV OS-F101 (m)
P1	945	1835	1640
P2	1160	2073	1838
P3	1370	2300	2029
P4	1580	2740	2396
P5	1740	3095	2709
P6	1740	3095	2448

Note : Corrosion allowance was used during operation.
Ovality = 0.75% per API 5L

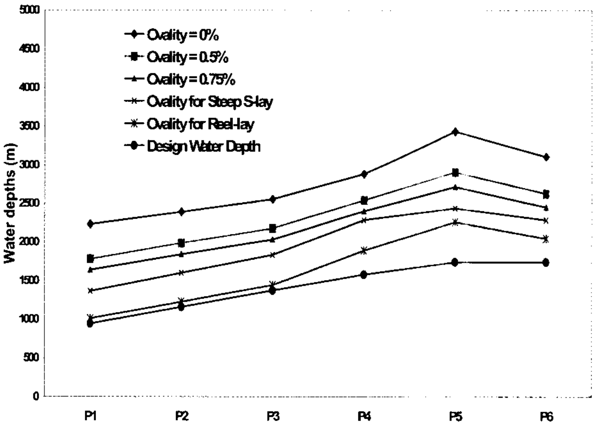

Fig. 2 Effect of pipe ovality on collapse water depth

5. Combined Load of Bending and External Pressure

5.1 Combined Load Design by API RP1111

The pipe selection should provide a pipe of adequate strength to prevent collapse (local buckling). Combined bending strain and external pressure load should satisfy the following:

$$\frac{\varepsilon}{\varepsilon_b} + \frac{(p_o - p_i)}{p_c} \leq g(\delta) \tag{11}$$

To avoid buckling, bending strain should be limited as ollows:

$$\varepsilon \geq f_1 \varepsilon_1 \quad (12a)$$

$$\varepsilon \geq f_2 \varepsilon_2 \quad (12b)$$

where,

$g(\delta) = (1+20\delta)^{-1}$ = collapse reduction factor

$\delta = \dfrac{D_{\max} - D_{\min}}{D_{\max} + D_{\min}}$ = API ovality = $2 \cdot f_o$

ε = bending strain in the pipe

$\varepsilon_b = \dfrac{t}{2D}$ = buckling strain under pure bending

ε_1 = maximum installation bending strain

ε_2 = maximum in-place bending strain

f_1 = bending safety factor for installation bending plus external pressure

f_2 = bending safety factor for in-place bending plus external pressure

$D_{\max}$ = maximum diameter at any given cross section

$D_{\min}$ = minimum diameter at any given cross section

Calculated water depth limits with 0.2% maximum nstallation bending strain are shown in Fig. 3. The calculated buckling water depths are deeper than design water depths.

5.2 Combined Load Design by DNV OS-F101

Pipe members subjected to have longitudinal compressive strain (bending moment and axial force) and external overpressure shall be designed to satisfy the following condition at all cross sections:

$$\left[\frac{\varepsilon_d}{\varepsilon_c/\gamma_\varepsilon}\right]^{0.8} + \frac{p_o}{p_c/(\gamma_{sc} \cdot \gamma_m)} \leq 1 \quad (13a)$$

$$D/t \leq 45 \quad \text{and} \quad p_i < p_e \quad (13b)$$

where,

ε_d = Design compressive strain

$\varepsilon_c = 0.78(\dfrac{t_2}{D} - 0.01)\alpha_h^{-1.5}\alpha_{gw}$

γ_ε = resistance strain factor

α_h = maximum allowed yield to tensile ratio

α_{gw} = girth weld factor

The combined load equations (13a) and (13b) are for a displacement controlled condition. In case of a load controlled condition, the other formula recommended by DNV should be used. Fig. 3 shows the combined load of 2% bending strain and external pressure during the installation. The calculated water depths are less than those obtained by API, but still deeper than maximum design depths. The water depths obtained by DNV code are controlling the final wall thickness design of the oil pipeline.

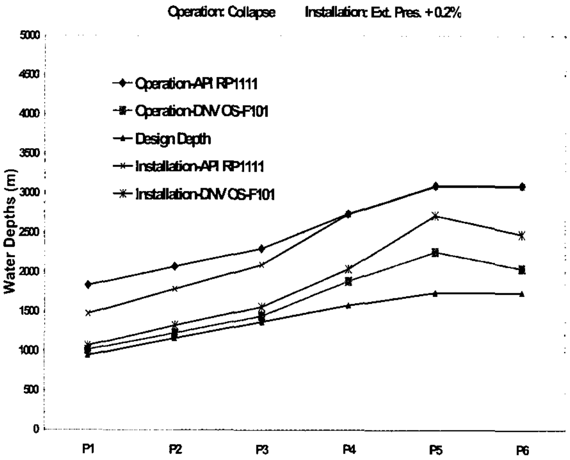

Fig. 3 Pipe buckling water depth

6. Concluding Remarks

1. Collapse buckling is very sensitive to the pipe installation method and pipe ovality. Collapse design by API code does not include the effect of pipe ovality. Therefore, collapse design by DNV code yields reasonable results.
2. Combined load design due to external pressure and bending by DNV code include an incremental power factor and additional three partial safety factors. Thus, DNV code yield too conservative results for deep water pipelines. Therefore, API code is recommended for the combined load design.
3. Mixed utilization of the DNV and API codes, as mentioned in item 2 and 3 above, will result a reasonable wall thickness design for deepwater pipelines.
4. It was found that the conservatism still exist within collapse prediction for deep water pipeline using the modern design codes such as DNV (2000) and API (1999).

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