Buckling Criteria for Subsea Pipeline

Abdul Khair, J.[a*], Jaswar, Koto[a], Affis Effendi[a], Ahmad Fitriadhy[b]

[a]Department of Aeronautics, Automotive and Ocean Engineering, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[b]School of Ocean Engineering, Universiti Malaysia Terengganu, Terengganu, Malaysia

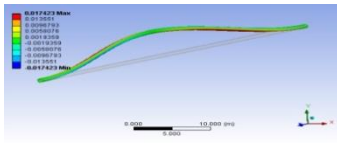*Corresponding author: abdulkhairjunaidi@gmail.com

Graphical abstract

Abstract

Oil and gas production in subsea operation continues to the extreme depth. Harsh environment and severe operation of oil and gas transportation due to high pressure and temperature become crucial for pipeline transportation. Consequently, The pipelines will deform to buckle shape which affect to integrity of pipeline. This phenomenon should be considered in design of pipeline to provide reliability of pipeline operation during time life period. The design result of pipelines is according to DNV F 101 whereas the magnitude of pipeline curvature will validate by ANSYS 14 to ensure pipeline reliability.

Keywords: Pipeline; buckle; expansion

■1.0 INTRODUCTION

Subsea production continues to the extreme depth of water. At this depth, the technical challenge of subsea system will be tight to comply with existing codes, moreover extreme pressure and temperature of crude oil is needed to transport from wet well to termination of loading. The pipelines are subjected to axial compressive forces which will cause the pipelines to expand, consequently the pipelines experience a deformation to buckle for certain size. Pipeline expansion should be allowed to accommodate the lateral movement of pipeline. Buckling is instability of pipeline structure that may be going to a failure if the curvature of buckling mode exceeds the pipeline strength.

■2.0 OBJECTIVE OF DESIGN

The objective is to provide acceptance design for subsea pipeline which focus on buckling mode related to load response due to pressure and temperature. To be able to understand the buckling phenomena, an initial imperfection of pipeline at designated location along the line will be defined. The selection of material, pipe wall thickness and pressure containment corresponds to the limit state design of pipeline which refers to API RP 1111 and the load effect to the structure will comply with DNV OS F101.

■3.0 LITERATURE REVIEW

Design of pipeline is required accurate test result for local buckling collapse subjected to bending loads which exceed the limit state of bending moment capacity. The minimum wall thickness is determined based on maximum allowable stress under design pressure. The design of pipeline is aimed to keep in safe during construction and operation and meet the life time period. The anomalous value of the axial tensile and compressive strain was obtained on the pipe test. Difference result derived from the test on pipe to the simple bending theory become design factor parameter to contribute to the understanding of crucial limit state for the design of onshore and offshore pipeline (F. Guarracino, 2007).

Subsea pipeline system operates under high pressure and high temperature (HPHT). Due to soil restraint, the pressure and thermal expansion can generate a significant level of compression that can cause global buckling in the pipeline. Global buckling is generally in lateral direction, although it can be started as an upheaval buckling. The two methods are applied to control the pipeline thermal expansion and lateral buckling by utilizing sleepers and buoyancy along the pipeline route. It uses two parallel positioned sleepers space in short distance. To further assess the pipeline buckling response and assist the selection of the thermal mitigation method, a series of numerical analysis were performed for a wet insulated single pipeline (WISP) through finite element analysis (FEA). The FEA model length was set for 3,000 m. Buoyancy length and buoyancy force are analysed against the critical buckling. The presented study indicated that both sleeper and buoyancy section can be the viable solutions for thermal load mitigation. (Jason Sun, Pauljukes June 2012.)

■4.0 DESIGN OF PIPELINE

The design of subsea pipeline must comply with the pipeline design codes such as ANSI/ASME B31.4, API RP 1111, DNV Design Guidelines. The pipeline standard gives the strict requirements for design, materials, construction, operation and maintenance to assure that the pipelines are safe to be operated during lifetime period without any failures or structure instabilities occurred such as buckling, fatigue, out of roundness and excessive free spans and etc. The DNV OS F101 gives the design requirement for pressure containment which is called Load Resistance Factor Design (LRFD). The LRFD principle refers to the design method in structural engineering that the actual load does not exceed the design resistance of the pipeline.

The DNV provides the formula to restrict compressive strain which does not exceed the design strain. The parameters are used include minimum internal pressure, external pressure and girth weld factor and choosing the value based on ratio D/T.

$$\varepsilon_{sd} \le \varepsilon_{Rd} = \frac{\varepsilon_c(t_2, p_{min} - p_e)}{\gamma_\varepsilon} \tag{1}$$

Where:

ε_{sd} = design compressive strain
$\varepsilon_c(t_2, p_{min} - p_e) = \quad 0.78\left(\frac{t}{D} - 0.01\right).\left(1 + 5.75.\frac{p_{min} - p_e}{p_b(t)}\right).\alpha_h^{-1.5}.\alpha_{gw}$
p_{min} = minimum internal pressure
p_e = external pressure, $\rho g h$.
$\alpha_h \quad = \left(\frac{R_{t\,0.5}}{R_m}\right)_{max}$
$\left(\frac{R_{t\,0.5}}{R_m}\right)_{max} = 0.93$

4.1 Pipeline Expansion

The amount of the pipeline expansion is an important design factor used in designing absorption devices such as loop or sleeper. The movement of pipeline expansion due to internal pressure and temperature are normally occurred in the pipeline, but the impacts of expansion movement will affect the pipe length at the end of pipeline. Forces result from internal load and temperature can be calculated as follow:

Force due to temperature change;

$$F_t = \alpha.E.A_s.\Delta T \tag{2}$$

Force due to pressure change;

$$F_p = P.A_i \tag{3}$$

Force due to Poisson contraction;

$$F_v = -v.A_s.\sigma_h \tag{4}$$

Force due to soil friction resistance;

$$F_f = \int_0^x \mu.W_s.dx = \mu.W_s.L_a \tag{5}$$

By equilibrium of the above forces for pipeline can be written:

$$F_t + F_p + F_v = F_f \tag{6}$$

The anchor length can be obtained using the above equation

$$L_a = \frac{1}{\mu W_s}(\alpha E A_s \Delta T + P A_i - v A_s \sigma_h) \tag{7}$$

The stress induced by the thermal and pressure expansion including the end cap effect can be written as:

$$\sigma_h = \frac{PD}{2t} \tag{8}$$

$$\sigma_{L1} = \frac{PA_i}{A_s} - \frac{\mu.W_S.x}{A_S} \qquad \text{if } x < L_a \tag{9}$$

This condition is for unrestrained line that the stress limitation to maintain the expansion stress σ_e should not exceed 0.72% of the SMYS.

$$\sigma_e = (\sigma_L^2 + 4\sigma_t^2)^{0.5} \le 0.72\sigma_y \tag{10}$$

4.2 Configuration of Buckling

When this expansion is restraint by axial friction between the pipeline and the soil furthermore an axial force will develop to be lateral movement in the pipeline. Subsea pipelines could buckle upward or sideway direction. The direction of movement will depend on the pipe-soil resistance and buckling constant is showed in Table 1. The effective axial force in the pipeline is given by:

$$P_0 = (1 - 2v)\frac{\pi}{4}D^2\Delta p + \pi DtE\alpha\Delta T \tag{11}$$

The configuration of the buckle can be calculated by solving the following expression for buckle length L,

$$P_0 = P + k_2\mu WL\left[\sqrt{1 + k_2\frac{EA\mu_i^2WL^5}{\mu(EI)^2}}\right] \tag{12}$$

P= Compressive effective axial force within the buckle, given by

$$P = k_1\frac{EI}{L^2} \tag{13}$$

The maximum amplitude of the buckle can be determined

$$y = k_4\frac{\mu_L WL^4}{EI} \tag{14}$$

The maximum bending moment is calculated by

$$M = k_5\mu_L WL^4 \tag{15}$$

Table 1 Buckling constant

Mode	k_1	k_2	k_3	k_4	k_5
1	80.76	6.391×10^{-5}	0.5	2.407×10^{-3}	0.06938
2	$4\pi^2$	1.743×10^{-4}	1.0	5.532×10^{-3}	0.1088
3	34.06	1.668×10^{-4}	1.294	1.032×10^{-2}	0.1434
4	28.20	2.144×10^{-4}	1.608	1.047×10^{-2}	0.1483

4.3 Temperature Profile

The temperature along a subsea pipeline is conducted by heat flow in the pipeline. The temperature should be maintained at certain temperature to avoid wax deposit on the pipe wall. Three types of temperature profile along the pipeline as shown in Figure 1 to Figure 3:
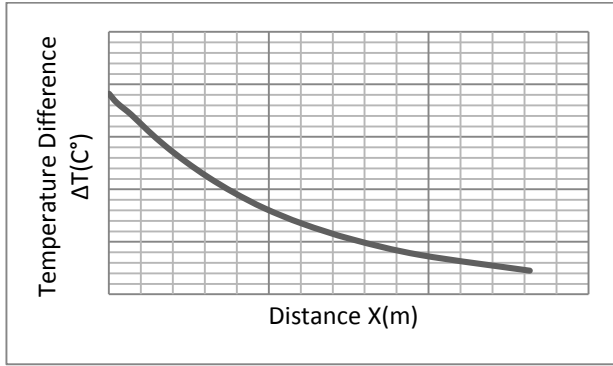
1. Exponential Temperature Decay

Figure 1 Exponential temperature decay
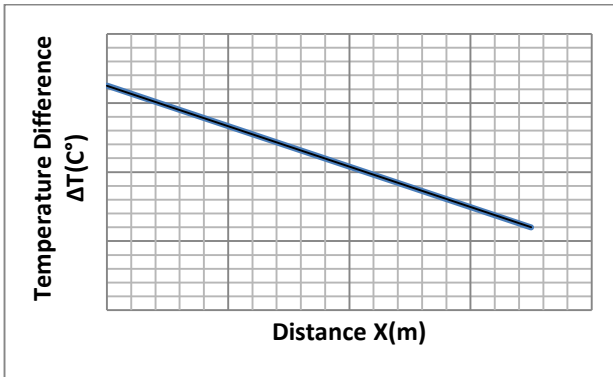
2. Linear Temperature Decay

Figure 2 Linear temperature decay
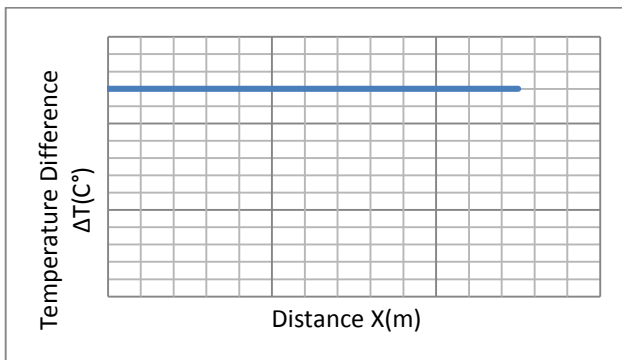
3. Uniform Temperature Decay

Figure 3 Uniform temperature decay

■5.0 ENGINEERING DATA

Input data comprise with Material properties of pipeline based on API 5L specification is shown at Table 2 (Pipeline Properties), operating condition and environment condition. High strength steel in grades X80 is selected to assist companies to assess in reducing pipeline weight and demand more economical transportation lines. This simulation refers to the behavior of material properties of grade X80 which experience imperfection as consequent of high pressure and temperature operation.

Table 2 Pipeline properties

Parameter	Unit	Value
Outside Diameter	mm	762
Wall thickness	mm	20*
Pipe Material Grade	-	X80
Steel Density	Kg/m^3	7850
SMYS	MPa	551
SMTS	MPa	620
Poisson ratio (v)	-	0.3
Young's Modulus (E)	GPa	207
Thermal Expansion Coef.(α)	C^{-1}	1.17E-05
Internal Pressure	MPa	15
External Pressure	MPa	10
Internal Temperature	^{0}C	70
External Temperature	^{0}C	10

Based upon the calculation of internal loads, that provides a simple model of one way buckling, the model is described in detail about the magnitude of curvature and maximum displacement of pipeline as shown in Figure 4.
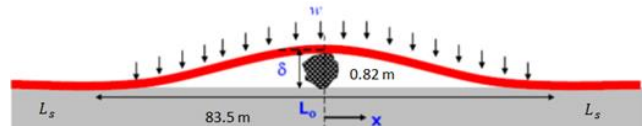

Figure 4 Buckle curvature

■6.0 PIPELINE MESH IN ANSYS

ANSYS Meshing provides multiple mesh control to generate a mesh and to set an option on how the geometries are meshed. The meshing automatically sets default mesh size on pipeline geometry. A 3D Finite Element model and mesh was created to obtain proper solution in pipeline design. The pipeline length is 83.5 meter and it is not complicated structure to generate mesh element size resulting 163152 nodes and 23296 elements.
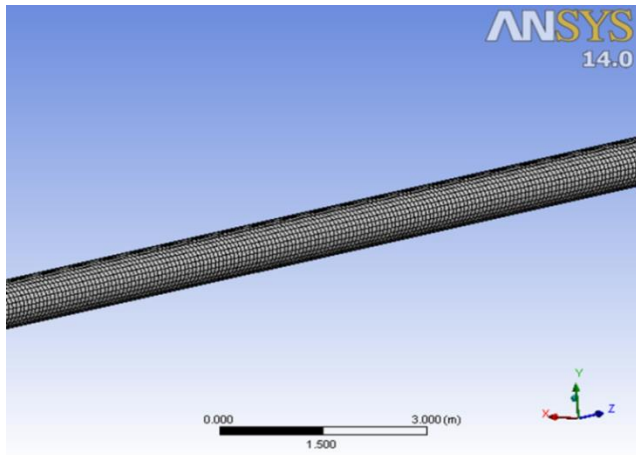
Figure 5 Pipeline mesh

7.0 RESULT AND DISCUSSION

ANSYS simulation were applied to the pipeline model as the Figure 6 shows pipeline deformation along with z-axis that subjected to axial compressive load. Large deformation indicates the elongations are occurred underneath the slope region whereas the upper side formed compressive deformation caused by buckle curvature upward.
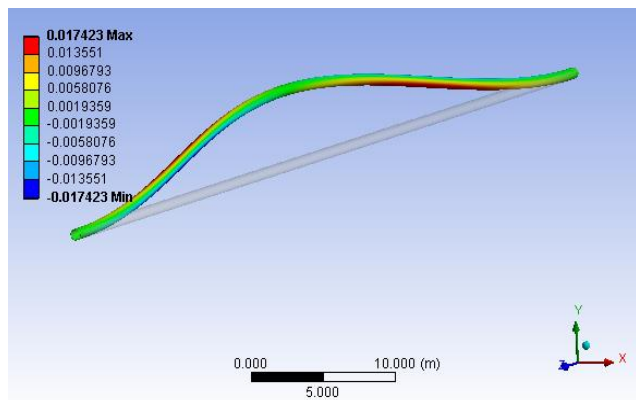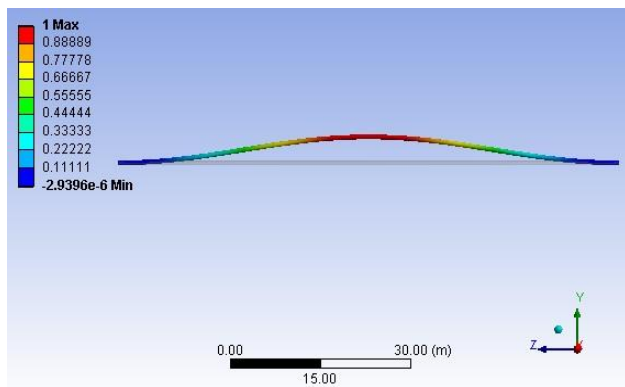

Figure 6 Deformation z-axis

Figure 7 Displacement y-axis

Pipeline expansion caused by pressure and temperature resulted vertical height of displacement at y-axis as shown in Figure 7. The maximum height of buckle curvature is 0.89 meter, whereas the results of theoretical design that the height of curvature as shown in Figure 5 (Buckle Curvature) is 082 meter.

8.0 CONCLUSION

Pipelines experience elongation due to high internal pressure and temperature to transport the crude oil. The design allows the pipeline expand lateral or upheaval at designated location to relieve the pipeline expansion. The design result is appropriate with ANSYS Workbench to validate the modeling.

Acknowledgement

References

[1] F. Guarracino, M. Fraldi, A. Giordano. 2007. *Analysis of Testing Methods of Pipelines for Limit State Design*. Dipartimento di Ingegneria Strutturale, Università di Napoli ``Federico II''. 80125 Napoli, Italy.

[2] Jason Sun, Pauljukes. 2012. *Thermal Expansion/Global Buckling Mitigation of HPHT Deepwater Pipelines Sleeper or Buoyancy.* International Offshore and Polar Engineering Conference, Greece June.

[3] Jaswar, Abdul Khair, J., H. A. Rashid. 2013. Expansion of Deep Water Subsea Pipeline. Applied in The International Conference on Marine Safety and Environment.

[4] Jaswar, Abdul Khair, J., Hashif. 2013. Effect of Axial Force Concept in Offshore Pipeline Design. The International Conference on Marine Safety and Environment.

[5] Palmer, A. C. and R. A. King. 2008. *Subsea Pipeline Engineering*. Pennwell Corporation.

[6] Palmer, D. Kaye and Associates. 1966. *Lateral Buckling of Subsea Pipeline; Comparison Between Design and operation*. A Division of SAIC Limited 13 Bon Accord Square United Kingdom.

[7] James, G. A. 1998. A Simplified Analysis of Imperfect Thermally Buckled Subsea Pipelines. *International Journal of Offshore and Polar Engineering*. 8(4): December 1998 (ISSN 1053-5381) Copyright © by The International Society of Offshore and Polar Engineers.

[8] Det Norske Veritas. D. N. V 2007. Offshore standard DNV-OS-F101: Submarine Pipeline Systems. Hovik, Norway: Det Norske Veritas, DNV.

[9] BAI, Y. and Q. BAI. 2010. *Subsea Engineering Handbook*. USA, ELSEVIER.

[10] Collberg, O. F. a. L. 2005. Influence of Pressure in Pipeline Design–Effective Axial Force. 24th International Conference on Offshore Mechanics and Arctic Engineering (OMAE 2005).