Marine Structures 59 (2018) 444–457

Contents lists available at ScienceDirect

Marine Structures

journal homepage: www.elsevier.com/locate/marstruc

Effect of proximity of imperfections on buckle interaction in deep subsea pipelines

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ARTICLE INFO

Keywords:
Lateral buckling
Subsea pipeline
Buckle interaction
Combined bending and external pressure
Cylindrical shell
Imperfection

ABSTRACT

Lateral buckling of pipelines with closely spaced imperfections laid on even seabed with non-linear soil-pipe interaction is investigated using finite element analysis (FEA). An analytical solution for lateral buckling of pipeline with single imperfection is proposed and is used to validate the FEA. Effects of amplitude, half wave-length and spacing of imperfections as well as soil resistance on lateral buckling response are presented. It is found that at imperfection spacing greater than half the imperfection half wave-length, there will be no interaction between the buckle lobes. Using validated FEA, the collapse of the pipe-wall due to the interaction between lateral buckling and external pressure is studied. Buckle interaction envelopes are developed and compared to recommendations of the DNV standard. It is shown that in pipeline with closely spaced imperfections, the lateral curvature at the onset of buckling is as large as the critical collapse curvature under combined bending and external pressure.

1. Introduction

Offshore oil and gas pipelines are subjected to high pressure and high temperature (HP/HT) from the inner hydrocarbon content during operation. Both the rise in temperature and internal pressure may cause longitudinal expansion of the pipeline. This expansion is restrained or semi-restrained by the pipe end devices and the soil which results in build-up of compression stresses in the pipe wall. The large effective axial force may cause formation of global buckle at pipeline locations with high out-of-straightness (OOS). Global buckling may occur in a vertical plane (upheaval buckling) or a horizontal plane (lateral buckling). The former is expected to occur in a buried or trenched pipeline and the latter is common if the pipeline is exposed on the seabed. Uncontrolled lateral buckling is not essentially a failure mode but can cause excessive deformation of the pipeline which could lead to localised buckling collapse, cyclic fatigue failure, fracture or hydrogen induced stress cracking [1]. For instance, the 1.3 million litres oil spill in Guanabara Bay (Brazil, January 2000) was triggered by the increase of pressure and temperature during operation condition which caused a lateral buckle with amplitude of 4 m and finally resulted in local buckle and rupture of the pipeline [2].

Early studies on global buckling were motivated by lateral buckling of railway tracks [3] using a differential equation approach. Probably Hobbs [4] was the first one to formulate lateral buckling of pipelines. A number of analytical, numerical and experimental studies on lateral buckling of subsea pipelines appeared since then, most notably are [5–12]. The analytical methodology proposed by Hobbs [4] has several limitations due to simplifying assumptions, such as linear elastic material behaviour, Coulomb friction soil model, small rotation theory and imposed post buckling configuration. However, Hobbs' [4] approach is well established in industry and is used as a concept design for susceptibility assessment of global buckling [13]. Hobbs [4] found that in global buckling, the pipeline can deform into four major modes (Fig. 1). Mode 1 requires concentrated lateral forces at each end of the buckle for equilibrium and is normally observed in upheaval buckling. In absence of these concentrated forces, the pipeline takes form of mode

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https://doi.org/10.1016/j.marstruc.2018.02.011
Received 9 November 2017; Received in revised form 22 January 2018; Accepted 26 February 2018
0951-8339/

Nomenclature

a_i	wrinkle amplitude bias
a_o	wrinkle imperfection base amplitude
D_0	pipe mean diameter, $D_0 = OD - t$
E	modulus of elasticity of the pipe
E_t	tangent modulus of elasticity of the pipe
F	axial load in the buckled region
f_0	ovalization ratio according to the DNV
F_y	yield force $F_y = \pi\sigma_y D_0 t$
f_y	yield stress in DNV
k	curvature
k_i	lateral imperfection curvature
k_c	critical curvature
k_{LTB}	lateral buckle curvature
L_B	Buckle half wave-length
L_G	spacing between lateral imperfection lobes
L_i	Imperfection half wave-length
L	length of the shell FE model
M_{LTB}	moment in the crown of the lateral buckle
M_p	plastic moment
M_{SD}	design moment
N	number of half-waves in wrinkle imperfection
OD	nominal outside diameter of pipe
OD_{max}	measured maximum outside diameter of pipe
OD_{min}	measured minimum outside diameter of pipe
P_C	collapse pressure
P_{el}	elastic collapse pressure
P_p	buckle propagation pressure
P_{PM}	Palmer and Martin propagation pressure
p_e	external pressure in DNV
Q	soil resistance in the lateral direction
R_i	soil resistance in the axial direction
r_i	soil axial resistance parameter
S_{SD}	design effective axial force
t	pipe wall thickness
W	lateral buckle shape
w_i	soil lateral resistance parameter
$\overline{W}$	initial sinusoidal imperfection of the pipeline
α_{fab}	fabrication factor in DNV
α_c	flow stress parameter in DNV
ν	poison's ratio
σ_y	yield stress
Δ_i	lateral imperfection amplitude
Δ	lateral buckle amplitude
Ω	ovalisation ratio
p_e	external pressure (used in DNV)
λ	wrinkle imperfection half-wave length
Υ	non-dimensional load
γ_m	γ_{sc} partial resistance factors in DNV
$\overline{\omega}$	localised wrinkle imperfection

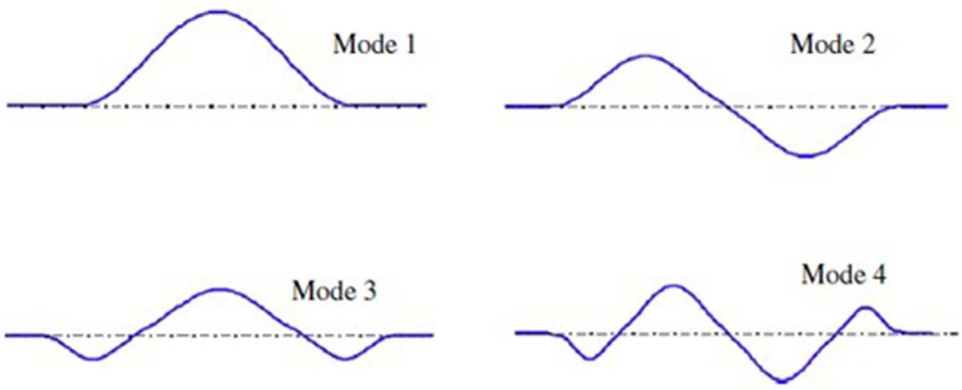

Fig. 1. Hobbs lateral buckling mode shapes [4].

3 during lateral buckle. Hobbs [4] noted that mode 3 is associated with highest bending moments and stresses in the pipe, however, asymmetric modes 2 and 4 (Fig. 1) can be triggered at lower axial forces compared to the symmetric mode 3. Maltby and Calladine [14] presented a simplified solution for lateral buckling of a pipeline with single imperfection on a rigid foundation with nonlinear soil resistance. They assumed bilinear and exponential constitutive models for the lateral soil resistance and found that the condition for localisation of buckling depends mainly on the limiting value of the soil resistance but not much on the exact constitutive law. Miles and Calladine [6] used a small scale experimental rig and observed that during formation of lateral mode 3 in Fig. 1, three distinct lobes develop and gradually approach a point of extinction. They suggested that the physical feature that caused lobes to stop growing was the axial friction that would have to be overcome in the active region of the growing lobes. Karampour et al. [8] conducted analytical and numerical investigations on the lateral buckling of pipelines with single imperfection and found that for a given imperfection amplitude, localisation will take place at a buckle half wave-length at which the axial force is equal to the Euler buckling force. The joint industry projects (JIP), HOTPIPE [15] and SAFEBUCK [16], launched in 2002 and concluded in 2015, established significant knowledge of the design of HP/HT pipelines susceptible to global buckling. The SAFEBUCK [16] study revealed that existing elastic models are excessively conservative and highlighted the necessity of performing FEA with nonlinearity in pipe material and soil properties. Using nonlinear FEA, Brown at al [17]. investigated the wrinkling mode of failure in the pipeline due to excessive bending and Karampour et al. [18–20] studied the interaction between lateral or upheaval buckling and propagation