Engineering Structures 172 (2018) 55–65

Contents lists available at ScienceDirect

Engineering Structures

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

Effective axial force in multi-layered cylinders with applications to insulated offshore pipelines

Knut Vedeld*, Håvar A. Sollund, Olav Fyrileiv, Leif Collberg, Olav Aamlid

DNV GL A/S, Veritasveien 1, 1363 Høvik, NO-0316 Oslo, Norway

A R T I C L E I N F O

Keywords:
Offshore pipelines
Effective axial force
Pressure
Temperature
Coating
Insulation
Upheaval buckling
Global buckling

A B S T R A C T

To ensure high content temperature, some offshore pipelines have insulation coating made from polypropylene or polyethylene. Typical coating systems have significantly lower stiffness than ordinary carbon manganese steel, but also significantly higher temperature expansion coefficients. Due to the differences in material properties, insulation coating systems have a non-trivial influence on the critical design parameter called the effective axial force in offshore pipelines. Current offshore design codes do not contain guidance on how to include the effects of coating systems on the effective axial force. In this paper, an exact analytical formula for the effective axial force in pipelines with arbitrarily many layers is deduced, accounting also for temperature variation along the radial coordinate. A simplified approximate formula, which is more suitable for use in engineering contexts, is developed and its validity verified by comparisons to results of the exact one.

1. Introduction

During their operational lifetime, offshore pipelines and risers will generally be subjected to varying internal pressures and temperatures, as well as external hydrostatic pressure. For a single layered, axially restrained pipeline it is rather simple to calculate how temperature expansion will affect the stress state in the pipeline and contribute to e.g., bending and buckling phenomena. In order to avoid complicated integration of pressures acting on the pipe-wall surfaces (which are generally doubly curved due to bending in the horizontal and vertical planes), the concept of effective axial forces, often referred to as effective tension in riser applications, has been used in offshore pipeline engineering for more than 40 years [1,2]. In brief, effective axial forces introduce pressure dependent corrections to “true” wall axial forces, i.e., forces obtained by integrating axial stresses over the pipeline cross-section [3]. The correction may be derived by application of Archimedes' principle for estimating buoyancy and submerged weight. It has been shown, in different manners, that effective axial forces, rather than true wall axial forces, govern second-order axial load effects [4–7] when treating a pipeline as a beam.

The effective axial force is a fundamental design parameter for offshore pipelines and risers, and is important for design aspects such as global buckling [8,9], upheaval buckling [10,11] and free-span design [12–16]. In fact, the design formulation in the world leading standard DNVGL-ST-F101 for the limit state of local buckling [17], which obviously is governed by the local (true) stresses, has been expressed using the effective axial force, illustrating the extent to which the concept of effective forces is integrated in modern offshore pipeline design.

For an offshore pipeline or riser, the maximum compressive effective axial force for an axially fixed pipeline is often conservatively applied for design calculations. In recognition of this, an equation for calculating the effective axial force for a single layer pipeline under fully axially restrained conditions is included in widely applied offshore pipeline design standards [17,18]. For buried pipelines, the main consequence of a too high compressive effective axial force is upheaval buckling [10,11]. The provisions in DNVGL-ST-F101 give instructions on how to calculate the maximum compressive effective axial force for pipeline-in-pipe cross-sections and bundles. However, for two-layered cross-sections, such as lined or clad pipelines [19,20], or multi-layered cross-sections where the layers are tightly bonded there are virtually no guidelines neither on how to estimate maximum compressive effective axial forces nor on how the presence of additional layers may affect stresses in the steel cross-section.

Lack of guidance for layered cross-sections may be unfortunate since pipeline cross-sections in most cases will be layered. For instance, internal liners or claddings of corrosion resistant alloy (CRA) are frequently used in pipelines with corrosive contents [19–23]. External coating systems are employed onshore and offshore to protect the pipelines against corrosion or impact or to provide thermal insulation

* Corresponding author.
E-mail address: knut.vedeld@dnvgl.com (K. Vedeld).
URL: http://www.dnvgl.com (K. Vedeld).

https://doi.org/10.1016/j.engstruct.2018.06.013
Received 23 October 2017; Received in revised form 13 April 2018; Accepted 5 June 2018
0141-0296/

[24]. For pipelines with insufficient submerged weight to ensure lateral stability under the action of waves and currents [25–27], the most common way of increasing their submerged weight is to apply a concrete coating, which, like thermal insulation, may be several times thicker than the pipeline steel wall itself. Apart from providing negative buoyancy, concrete coating may also contribute to protect a pipeline against impact e.g., from trawl gear, anchors or dropped objects [28,29]. Hot applied enamel coatings, typically consisting of a mixture of asphalt (bitumen) and fiberglass, are commonly preferred external corrosion coatings for pipelines provided with concrete weight coating [24]. For pipelines without concrete coating, both a mono-layer of fusion-bonded epoxy and a three-layer system, comprising an epoxy primer, a polyethylene adhesive and a topcoating of polyethylene, polypropylene or polyurethane, are commonly used [30], with polypropylene being the dominant material of choice. Typical thermal insulation coatings may consist of polyurethane or polypropylene foam with a high-density polyethylene or polypropylene outer layer. The use of syntactic foams for thermal insulation (foams with embedment of hollow, typically glass or aluminum, spheres in a polymer matrix) may in some cases be required for external pressure resistance in deep water applications [31].

It is not straightforward to estimate how liners and external coatings affect overall resistance and load effects. Consequently, including additional layers in pipeline design calculations is not obvious either. The mechanical influence of external coatings on pipeline steel is generally not considered in design standards, which merely state that possible strengthening effects of internal or external coatings shall not be utilized in the characteristic resistance, unless properly documented. In response to lack of guidance, Vedeld et al. [32,33] derived closed-form analytical expressions for displacements and stresses in two-layer cylinders subjected to pressure and thermal loading for relevant axial boundary conditions, and studied effects of a liner or clad layer for different load cases. Analytical two-layer expressions were then applied to develop analytical formulae, as well as a simplified approximate formula, for effective axial forces in lined and clad pipelines [6,7], concluding that effects of liners and cladding on effective axial forces were non-negligible.

Mechanical response of multi-layered and thick-walled cylinders to pressure and thermal loading has been widely studied, since multi-layered cylinders have a broad spectrum of industrial applications. Layered cylinder designs are, not only applied for pipelines, risers [34] and piping systems [35,36], but also as pressure vessels in the field of high pressure technology, e.g., in chemical and nuclear plants, for gas storage, in fertilizer production, and in hydraulic and forging presses [37–40]. Research on thermoelastic response has covered a range of conditions, including uniform thermal stresses and loading from steady-state temperature distributions [40,41], time-dependent thermal stresses [42–45] and thermal shocks, which may be challenging to piping systems with multi-phase flow [35,46].

The stress state in a thick-walled cylinder subjected to uniform internal and external pressure was determined by Lamé already in 1831 [47]. Based on Lamé's solution, Xiang et al. [48] and Shi et al. [49] derived a simple and convenient recursive algorithm for obtaining the exact stress state of a multi-layered pressurized hollow cylinder in plane stress and plane strain conditions. The recursive algorithm proposed by Xiang et al. and Shi et al. was later extended by Sollund et al. [50] to include radially varying thermal stresses, and Vedeld and Sollund [51] developed a new recursive algorithm for heated pressurized multi-layered cylinders in generalized plane strain conditions.

The main objective of the present study is to develop an exact analytical formula for effective axial forces in axially restrained multi-layered offshore pipelines. The deduction is made possible by the recursive algorithm for stresses in heated, pressurized multi-layered cylinders under plane strain conditions, developed by Sollund et al. [50]. A simpler, approximate formula will also be deduced. The novel formulae for effective axial forces in multi-layered pipelines will be applied to a set of actual offshore pipeline designs to study the extent to which coating layers may influence effective axial forces. Potential consequences of current industry practice of ignoring the contributions from coating layers to effective axial force predictions will be discussed based on the case studies. Finally, the approximate formula will be tested for accuracy and evaluated for typical engineering purposes.

2. Problem definition

2.1. The effective axial force concept

The concept of effective axial forces has been discussed in detail previously, e.g. in [4–7] and proven experimentally by Palmer et al. [52]. Therefore, the concept will only be briefly described herein. The effective axial force S_{eff}, which governs the global buckling response and geometrical stiffness of the pipeline, is given by (see e.g. [3] or [7]):

$$S_{eff} = N - p_{int} A_{int} + p_{ext} A_{ext}, \tag{1}$$

where N is the true wall axial force, p_{int} is the internal pressure, A_{int} is the internal cross-sectional area of the pipeline, p_{ext} is the external pressure and A_{ext} is the external cross-sectional area.

For a pipeline with end-caps, completely unrestrained in the axial direction, the effective axial force becomes

$$S_{eff} = 0 \tag{2}$$

While Eq. (2) represents the boundary value for an axially free pipeline (see e.g. [5]), the other boundary value - for a totally restrained single-layer pipeline without end-caps, is given by

$$S_{eff} = H_{eff} - \Delta p_{int} A_{int} (1-2\nu) - EA_s \alpha \Delta T, \tag{3}$$

where H_{eff} is the effective residual lay tension, Δp_{int} is the change in internal pressure relative to laying, ν is the Poisson's ratio of the pipeline steel, E is the Young's modulus of the pipeline steel, A_s is the pipeline steel cross-sectional area, α is the temperature expansion coefficient and ΔT is the change in temperature relative to the time of laying. Eq. (3) is an important equation for pipeline design practice, and may be found in several offshore standards and recommended practices [9,17,18,53]. A formal proof of Eq. (3) has been given e.g. by Vedeld et al. [7].

When a pipeline is installed on the seabed, the as-laid effective force is balanced by the lay vessel tension. The effective tension on the seabed includes the actions of external pressure on the pipeline, implying that effects of external pressure are included in the residual lay tension term [4,7]. Furthermore, when an installed pipeline is pressurized yet restrained axially, the Poisson effect will alter the true wall tension due to a combination of radial expansion and axial restraint. This true wall tension is seen in the 2ν factor on the internal pressure term in Eq. (3). The temperature expansion term in Eq. (3) is as expected for an axially restrained pipeline, and not affected by pressure. While Eq. (3) is only valid for an axially restrained pipeline, Eq. (1) is boundary condition independent. In other words, Eq. (3) is a special case (and maximum compressive limit) of Eq. (1), and it can hence be demonstrated that (see e.g. [4]):

$$S_{eff} = H_{eff} - \Delta p_{int} A_{int} (1-2\nu) - EA_s \alpha \Delta T = N_{tr} - p_{\mathrm{int}} A_{\mathrm{int}} + p_{ext} A_{ext} \tag{4}$$

As a special case of Eq. (3), one should notice that in the as-laid condition, when the internal pressure, external pressure and temperature remain the same as when the pipeline was laid, the effective axial force becomes

$$S_{eff} = H_{eff}. \tag{5}$$

Thus, before operational loads are applied, the effective axial force equals the effective lay tension, which also follows directly from horizontal force equilibrium, as shown by Fyrileiv and Collberg [4].

It should be noted that Eqs. (2) and (5) are valid for any pipeline cross-section, layered or otherwise. The "true"-wall axial force N