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Second-order analysis of an imperfect corroded tubular member on a two-parameter elastic foundation

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ABSTRACT

This paper presents a method for the second-order elastic and stability analyses of a corroded tubular member with initial geometric imperfections, resting on a two-parameter elastic foundation. It is assumed that the member is a simply supported Euler–Bernoulli beam-column with a corroded, yet compact cross section. Corrosion is modeled as symmetric loss of wall thickness that varies in magnitude along the member length. Moreover, the member is loaded both axially, transversely and simultaneously subjected to internal and external pressures. Despite all the effects considered herein, this model neglects the effects of thermal loads and torsion, as well as shear and axial deformations along the member. The fourth-order boundary value problem that governs the second-order elastic behavior of the tubular member is solved using the Galerkin method. The proposed method and corresponding equations are used to obtain the second-order transverse deflections, as well as the bending moment and shear force diagrams. This method is also used to estimate the buckling load and compressive strength of the tubular member, which play an important role in the design of tubular structures. The accuracy and effectiveness of the aforementioned formulation are evaluated using four comprehensive examples. The results from the examples demonstrate that the proposed method can be used in the analysis and design of submerged or non-submerged tubular members at a low computational cost.

1. Introduction

Submerged and non-submerged pipes as well as structures made of tubular members are widely used in the oil, nuclear, hydroelectric, and petrochemical industries among others. These structures are susceptible to corrosion and its adverse effects can cause billions of dollars in losses. For example, the catastrophic failure of an oil pipeline due to corrosion might cause oil leakage to the environment, with devastating economic and environmental consequences. Significant savings in corrosion-related extra costs can be attained if pipes are inspected periodically to detect any significant deterioration that might jeopardize their structural integrity. However, the costs associated with pipeline inspection are relatively high. An attractive alternative to reduce corrosion-related costs is through determining the remaining in-service life of the corroded pipeline. This can be achieved by determining the remaining capacity of the pipeline after corrosion. Technical standards such as the ASME B31G [1] and the DNV-RP-F101 [2] discuss the importance of establishing the remaining capacity of pipes with corroded sections.

Pressure is an important load that may lead to pipeline failure by yielding, fracture or even buckling. The API 579 [3] fitness-for-service guideline presents several methodologies to assess quantitatively the structural integrity of in-service pressurized equipment when a flaw or damage might be present. In practice, tubular members, pressure vessels, and all components under pressure are designed considering a certain corrosion allowance, as discussed by section VIII of the ASME's Boiler and Pressure Vessel Code in divisions 1 [4] and 2 [5]. They also provide requirements for their design, fabrication, inspection, testing, and certification.

From the aforementioned discussion, it is known that tubular members are highly affected by corrosion and pressure. Moreover, they are also affected by many factors like loading and boundary conditions, foundation support and initial geometric

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Nomenclature

A_e	external area of the cylinder wall
A_i	internal area of the cylinder wall
A_s	cross-sectional area of the cylinder wall
b	Buoyancy force
C	unknown constants used in the weighted residual method
E	modulus of elasticity
e	distance between the centroids of the element (original and corroded)
F_{v1}	transverse load caused by the internal pressure acting on an infinitesimal pipe element
F_{v2}	transverse load caused by the external pressure acting on an infinitesimal pipe element
h	member span
I_0	moment of inertia of the corroded pipe cross-section in relation to the original position of the centroid
I	moment of inertia of the corroded pipe cross-section in relation to the modified centroid
k_s and k_G	two parameters of the elastic foundation (ballast modulus k_s, and transverse modulus k_G)
M	bending moment
P	axial force
p_e	external pressure
p_i	internal pressure
P_v	axial force on the pipe resulting from the longitudinal stress caused by the hoop stress and Poisson effects
Q	applied total lateral load
R	residual of the approximation obtained by weighted residual method
R_{ex}	external radius
R_{int}	internal radius
R_{max}	maximum external radius
u	lateral deflection of the centroidal line of the tubular element
u_{ap}	approximated lateral deflection of the centroidal line of the element obtained by weighted-residuals method
u_{ins}	initial geometric imperfection of the tubular element caused during its installation
u_{inp}	sum of the initial imperfections of the tubular element caused during the installation and asymmetric corrosion
V	shear force
w	weight functions used in the weighted residual method
x	coordinate along the centroidal axis of the tubular element
w_{fluid}	internal fluid weight
w_{steel}	dry steel weight
γ_{st}	specific weight of steel
γ_{fluid}	specific weight of internal fluid
γ_{sea}	specific weight of sea water
ε	maximum loss of wall thickness
η	corrosion pattern parameter
θ	angular coordinate of the tubular element
ν	Poisson's ratio
ϕ	basis functions used in the weighted-residuals method
Λ	differential operator defined in Eq. (21)
Ω	function of the independent variables defined in Eq. (21)

imperfections. A thorough understanding of all these effects is essential for assessing the structural integrity and predicting their in-service life of pressurized corroded pipes. Some studies are available in the technical literature that deal with these effects on tubular members some of which are briefly presented next.

Maxey et al. [6] developed a criterion to evaluate the remaining strength of corroded pipes that considers a longitudinal surface flaw to predict the hoop stress level at failure. Another method to evaluate the remaining strength of corroded pipes was found by Kiefner and Vieth [7]. Zheng et al. [8] and Chen et al. [9] conducted studies to determine the flexural capacity of pipes including corrosion and internal pressure effects. Lutes et al. [10] investigated the relationship between compressive strength and loss of wall thickness of a tubular member. In this study, Lutes et al. [10] indicated that the requirements provided by the American Petroleum Institute [11] are sufficiently conservative for the design of tubular members. All the studies provide some insight in understanding the behavior corroded tubular members; however, all of them assume that the pipe has no initial geometric imperfections.

Based on previous studies by the authors, it is believed that initial geometric imperfections can significantly affect the mechanical behavior of tubular members. For instance, Smith-Pardo and Aristizabal-Ochoa [12] and Aristizabal-Ochoa [13], developed analytical models to study the second-order deflections of beam-columns with initial geometric imperfections. In these studies, closed-form expressions were derived and it was found that the transverse deflections, bending moments and shear forces are highly influenced by initial imperfections.

Furthermore, it is known that pipelines are often in contact with the supporting soil. Therefore, soil-structure interaction is another factor affecting the mechanical behavior of tubular members, which needs to be investigated. Structural engineers have traditionally used elastic foundation models to perform inexpensive simulations of soil-structure interaction. Two well-known elastic foundation models are those of Winkler and the two-parameter model. The former replaces the soil by independent springs (Winkler springs) with the reaction forces of the soil depending on the beam deformation only; that is, the force of each spring is independent from those of the neighboring springs. The latter is a more accurate model which allows for interaction between the Winkler springs, and is suitable for many practical applications. These two models have been used in a multitude of studies [14–25].

The analytical models available in the current technical literature ignore the effects of both initial geometric imperfections and elastic foundation in the mechanical behavior of corroded tubular members. Consequently, the main objective of this paper is to present an analytical model capable of predicting the behavior of a corroded and imperfect tubular member, subjected to transverse and axial loads as well as to internal and external pressures. The tubular member is supported on a two-parameter elastic foundation. In addition, this element is assumed as simply supported, and the corrosion is modeled as loss of wall thickness. The loss of wall thickness of the cross section is assumed symmetric with respect to the vertical axis and the amount of corrosion is assumed to vary in magnitude along the tube span. This model considers external corrosion, but effects of internal corrosion are not included. The governing differential equation is solved using the Galerkin method. The proposed model can be used the analysis and design tool for submerged or non-submerged tubular members at a lower computational cost when compared to FEM simulations.

The remainder of this paper is organized as follows: first, the structural model is described, followed by the derivation of the