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On elastic-plastic collapse of subsea pipelines under external hydrostatic pressure and denting force

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ABSTRACT

This paper presents analytical and numerical researches on the buckling or collapse of offshore pipelines under external hydrostatic pressure. Firstly the case of homogeneous ring model is investigated followed by a detailed study on corroded rings. The elastic-plastic collapse pressure could be treated as the least root of an elementary function. We prove that collapse pressure is a strictly increasing function of mode number in this paper and present some interesting structures of the roots. Partially corroded ring is parametrized by corrosion depth and angle extent. A comprehensive comparison shows that plasticity should not be neglected when the ring is thick-walled. Moreover, a study on large deflection deformation of 3D cylindrical shells quasi-statically dented under constant external pressure is carried out theoretically and numerically. The buckle propagation pressure is shown to be a meaningful value to normalize external pressure. This paper serves to enhance the understanding of destabilizing effect of external pressure mainly applicable and relevant to subsea offshore industry.

1. Introduction

Undersea pipelines play a pivotal role in the modern offshore industry. Although initial investment is by no means trivial, pipelines enjoy the advantages of efficient transportation, minor maintenance and long lifespan. A direct contrast with the land pipelines is that the subsea pipelines are expected to be loaded under external pressure while land pipelines are often designed to meet the blast criterion due to internal pressure. Bursting failure induced by internal pressure is only important for pipe laid in relatively shallow water for the offshore engineering. Although it published many years ago, ASME B31G [4] is the still most popularly used standard on determining the bursting failure pressure of intact or corroded pipes. To be more recent, DNV-RP-F101 [2] published methods on assessing the safety of internally pressurized intact and corroded pipelines. The main feature of DNV document [2] is that the interactions of several corrosion defects, combined loads including internal pressure and longitudinal axial compression, and the complex shapes of corrosion pits could be accounted for. The bursting pressure of intact or corroded pipes has attracted many researches recently. For example, Netto [3] conducted a bursting test of a wall-thinned pipe and by FEM analysis developed an empirical equation for engineering application. Masayuki [1] used the experimentally verified 3D FEM to study the bursting of pipe with wall thinning for three kinds of materials: line pipe steel, carbon steel and stainless steel and finally concluded that existing criterion for line pipe steel is also applicable to the carbon steel and stainless steel. However instability rather than the strength insufficiency is an essential cause of failure destroying the structural integrity of whole pipeline system, i.e., instability often occurs with the maximum stress lower than yielding stress. The loss of stability often induces two instant catastrophic results: local buckling and buckle propagation [5]. Without proper arrest of buckle propagation, a wide range of the pipeline collapses as a whole. Many researches have been directed to design more reliable buckle arrestors, e.g., integral type [6,7], slip-on type [8], internal ring type suitable for pipe-in-pipe structures [9]. Although buckle propagation could be arrested by installation of proper buckle arrestors, the potential disasters including leaking of oil and pollution of environment or possible casualty make local buckle an absolutely unaccepted failure mode [10].

Actually in-situ pipelines may be imperfect with thickness reduction due to corrosion, initial ovality. The subsea hazardous environment makes the pipelines susceptible to corrosion and erosion. It has been concluded that the critical pressure of steel pipes is sensitive to imperfection [11]. For partially corroded shells, there exist some recent relevant investigations. Netto [12] studied the influence of a local corrosion pit on the critical collapse pressure

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by experiments and finite element analysis. Moreover the effect of corrosion depth and the extent of the corrosion pit on cross-section collapse pressure was investigated in a following parametric study. Netto [13] also studied the case of long and narrow corrosion defects in a similar manner. A comprehensive research was conducted by Sakakibara [14] experimentally and numerically. It was found that the collapse pressure was reduced by 50% when corrosion groove was about 50% of the wall thickness in depth. Insightful analytical researches were carried out by Xue [15,16], Bai and Hauch [17] and Fatt [18]. They represented the corrosion by corrosion depth and angular extent. In a previous publication by Yan et al. [19], it was found that both Xue and Fatt [16] and Fatt [18] neglected the mid-surface in extension condition and after inclusion of this condition the accuracy of the analytical model could be improved. Indeed the above models are based on the so-called Levy-Timoshenko [20,21] approach for circular rings under external hydrostatic pressure. Very recently Fraldi [22–26] refined the Levy-Timoshenko method in a series of papers, oriented towards better assessment of collapse pressure of UOE pipes (commonly used in offshore industry, see Kyriakides and Corona [11]). Their derivation was mainly based on the very fact described by Kyriakides and Corona [11] that offshore pipelines were much thicker with D/t (diameter-to-thickness ratio) ranging from 50 for shallow waters down to 15 for deep waters and even lower for high pressure flow. So plasticity may occur before the critical collapse load is reached. Fraldi et al. [23] refined the Levy-Timoshenko approach by including the tangent plastic modulus instead of elastic modulus and derived a closed-form solution of critical pressure for homogeneous rings. Fraldi et al. [23] further showed the improved accuracy achieved by comparison with classic Timoshenko solution. An interesting finding was described that the critical pressure for every buckling mode number n was smaller than a constant which was below the fully plastic pressure. Although Fraldi [22,23] finally proved this result by an indirect method, it was tried but later thought "impractical by the strongly non-linear dependence of the tangent modulus on the pressure" to prove directly the fact that the critical pressure was strictly increasing function of the mode number. In this paper we prove this monotonicity and further present some structures of the roots of the closed form solution by Fraldi et al. [23]. This effort should enhance the understanding of Fraldi's solutions. We then move forward towards the assessment of inhomogeneous rings including the effects of partial corrosion. We find that corrosion effect could be investigated under the same framework of classic Levy-Timoshenko formulation. Later we observed the possibility of anti-symmetric modes may occur apart from the symmetric modes.

The remaining part is concerning the response of shells under combined denting force and external pressure. In some accidental cases, the pipelines could be impacted due to human interference by unexpected dropping objects [27] from a platform or a vessel anchor. The usual result is a local dent. The existence of local dents significantly reduces the load carrying capacity of pipelines [11,28]. Kyriakides and Corona [11] in their monograph pointed out that a shallow dent with depth of 10% diameter reduced the collapse pressure by 50%. Ramasamy and Ya [28] carried out detailed finite element analysis on the collapse pressure and buckle propagation of dented tubes and recommended FEM as a robust tool in collapse analysis of dented tubes. In practical design phase, the sizes of dents are not presumed but usually from a denting force-deflection curve [29]. The determination of load-deflection curve has attracted many researches. Due to the nature of large deflection, plastic energy dissipation is much more important than elastic strain energy [30]. The rigid plastic model thus is usually adopted in developing simplified prediction curve. Firstly, ring model was used and investigated analytically, numerically and experimentally without accounting for 3D effects motivated by the wide use of energy absorbers. For example, DeRuntz and Hodge [31] used the four stationary plastic hinge method by rigid plastic constitutive model in the absence of plastic hardening in analyzing the ring compressed by two flat plates. Reid and Reddy [32] modified the cross-section to include the effect of plastic hardening. A detailed comparison with an experimental result [33] revealed that accounting for plastic hardening resulted in improved accuracy. Obviously oriented towards the optimization of energy absorbers, the above researches do not include extra loads such as pressure. A crack at the problem concerning the effect of pressure is by Karamaous [34]. Karamanous [34] investigated the case of externally pressurized ring under two opposite radial concentrated forces. Recently Hyde et al. [35–37] studied the collapse of partially supported ring subjected to concentrated denting force in the presence of external pressure. The external pressure's destabilizing effect was observed by both researchers. Strictly speaking, 3D shell model should be used in calculating the force-deflection curve. 3D elastoplastic FEM is often used due to the complex nature of shell kinematics. Brooker [38] used FEM calculating the response of continuously supported shells under single transverse denting force and derived an empirical function representing the force-deflection curve by curve fitting procedures. Zeinoddini et al. [27] further considered the effect of flexible soil supports and conducted comprehensive FEA on the sea bed flexibility for long pipelines with internal pressure considered. The soil material was represented by classical modified Drucker-Prager/Cap plasticity model. The pipes resting on a stiffer seabed were found to be more vulnerable to the impact damage.

Although complex and systematic finite element analysis procedures are recommended by DNV-RP-F111 [29], Błachut and Iflefel [39], Yong Bai and Qiang Bai [40], simple formulas from theoretical rigid plastic analysis are more feasible as to realistic engineering application. Wierzibicki and Suh [41] put forward an energy balance based rigid plastic model under single transverse denting force in the presence of axial load and bending. The main novelty lies in successful separation of dissipated plastic energy into contributions from rings and generators. Basing on this model, Karamanos and Andreadakis [42] included the contribution of internal pressure with Arabzadeh and Zeinoddini [43] further considering the effect of elastic supports. Illuminated by research by Hoo Fatt [44], Karamanos and Eleftheriadis [45] adopted the methodology by Wierzibicki and Suh [41] and derived a formula representing the relationship of denting force and radial deflection of the middle cross-section under external pressure. Although their derivation seems to be concise and reveals that the external pressure magnitude should be normalized by the propagation pressure, their formula gives zero force when the shell is loaded by external pressure equal to the characteristic buckle propagating pressure. Since the propagation pressure is often about 20% of the local buckling pressure [418], the stiffness against the denting force should not vanish when deflection is not very large. So their results are not applicable when the external pressure has exceeded the propagation pressure. In this paper, the above problem is solved and we find that indeed when radial deflection is not very large, the denting force should not be zero. Furthermore, we conclude the steady propagation pressure is an important and meaningful value nondimensionalizing the external pressure for large deflection analysis of shells.

This paper is mainly composed of two parts. In Section 2 we discuss the small-deflection elastoplastic response of a ring or infinitely long shell under purely external pressure analytically. This is an extended research after Yan et al. [19] and Fraldi and Guarracino [25]. In Section 3, we discuss the large-deflection plastic response of a cylindrical shell under combined denting force and the external pressure. This paper should enhance the under-