Ocean Engineering 146 (2017) 87–100

Contents lists available at ScienceDirect

Ocean Engineering

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

Elastic-plastic fracture analyses for misaligned clad pipeline containing a canoe shape surface crack subjected to large plastic deformation

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ARTICLE INFO

Keywords:
Canoe shape
Crack tip opening displacement (CTOD)
Failure assessment curve
Weld misalignment
Pipeline
Surface crack

ABSTRACT

Offshore pipelines are subjected to large plastic deformation during the reeling stage or in-service operation. These pipelines are joined together by a welding process, and defects and weld misalignment are frequently introduced into the pipelines, posing tremendous challenges to the integrity of these pipelines. In this study, the fracture responses of misaligned clad pipeline containing a canoe shape surface crack located in weld centre line (WCL) and fusion line (FL) were investigated using 3-D elastic-plastic finite element (FE) analyses. The influences of crack depth ratio, crack length to perimeter diameter ratio and centerline offset ratio on the crack tip opening displacement (CTOD) were analyzed in detail. The relationship between the CTOD and the global strain (ε_g) was built up, and a linear relationship was observed for ε_g ranging from 0.6% to 2%. The fracture assessment equation of British Standard (BS) 7910 predicted an over-conservative result in comparison with that obtained by FE analyses. Therefore, a new strain-based failure assessment curve was developed to assess the fracture behaviour of misaligned clad pipeline subjected to large plastic deformation.

1. Introduction

In recent years, the demand for recoverable corrosive hydrocarbons has increased dramatically. Hence, a corrosion resistant double walled pipeline, referred to as clad pipeline, is widely used to transport these natural resources. The pipeline consists of an outer carbon steel pipe providing the load capacity and an inner corrosion resistant alloy (CRA) liner protecting the outer pipe from corrosion. The pipelines are constructed by joining one end of the pipe to the other end by girth welding process, and potential cracks are usually detected to initiate from the welding region. Weld misalignment, centreline offset misalignment or angular misalignment, is also invariably introduced into the pipeline during the welding process. In addition, during the reeling stage or in-service operation, the pipeline undergoes large plastic deformation up to the order of 2% (Hilberink, 2011; Tkaczyk et al., 2011), increasing the risk of crack initiation and propagation. Therefore, it is imperative to assess the structural integrity of the misaligned clad pipeline containing a surface crack under large plastic deformation.

In elastic-plastic fracture regime, *J*-integral and crack tip opening displacement (CTOD) are frequently used to assess the fracture responses of cracked configurations, and considerable research has been conducted to investigate the fracture behaviours for various geometries and loading conditions (Chiodo and Ruggieri, 2010; Hertelé et al., 2014; Jayadevan et al., 2004, 2006; Kim et al., 2002; Nourpanah and Taheri, 2010; Pépin et al., 2015; Paredes and Ruggieri, 2015; Parise et al., 2015; Souza and Ruggieri, 2015; Souza et al., 2016). Kim et al. (2002) established the fully plastic *J* estimation equations of part circumferential surface cracked pipes based on EPRI *J*-estimation procedure and reference stress approach. However, the above research is based on small strain theory and the effect of weld strength mismatch is not considered. According to finite strain theory, Jayadevan et al. (2004) and Østby et al. (2005) investigated the fracture responses of cracked pipelines subjected to large plastic deformation, and a linear relationship between CTOD and global strain was built up. The fracture assessment for circumferential cracks in girth welded pipelines was conducted by Paredes and Ruggieri (2015), and various weld mismatch ratios were included in the parametric study to account for the effect of weld strength mismatch. It is worth noting that above research works are all about fracture analyses of aligned configurations. For misaligned ones, British Standard (BS)7910 (2013) presents the following assessment equation to evaluate the effect of weld misalignment on the fracture responses of cracked structures:

$$K_{\mathrm{I}} = Mf_{\mathrm{w}}\{k_{\mathrm{tm}}M_{\mathrm{km}}M_{\mathrm{m}}P_{\mathrm{m}} + k_{\mathrm{tb}}M_{\mathrm{kb}}M_{\mathrm{b}}[P_{\mathrm{b}} + (k_{\mathrm{m}} - 1)P_{\mathrm{m}}]\}\sqrt{\pi a} \tag{1}$$

where K_{I} is the Mode-I stress intensity factor, a is the crack depth, M is the bulging correction factor, f_{w} is the finite width correction factor, k_{tm} and

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https://doi.org/10.1016/j.oceaneng.2017.09.058
Received 16 January 2017; Received in revised form 18 July 2017; Accepted 24 September 2017

k_{tb} are the membrane and bending stress concentration factors, respectively, M_{km}, M_{kb}, M_m and M_b are the stress intensity magnification factors, k_m is the stress concentration factor induced by weld misalignment, P_m and P_b are the primary membrane stress and bending stress. In fact, the above assessment equation uses fracture parameters of aligned configurations to assess the corresponding parameters of misaligned ones by taking into account k_m based on the superposition method (Andrews, 1996). Therefore, considerable effort has been made to develop k_m equations for a wide range of geometrical structures (Bock and Zeman, 1994; Brabin et al., 2010; Cui et al., 1999; Lotsberg, 1998, 2008, 2009; Zeman, 1994). However, for pipelines subjected to large plastic deformation, the assessment equation given by BS7910 (2013) usually predicts an over-conservative result in comparison with that obtained by finite element (FE) analyses. Therefore, in this study, the fracture assessment of misaligned clad pipeline containing a canoe shape surface crack is investigated using 3-D elastic-plastic FE analyses. In Sections 2 and 3, the geometrical details, material properties and FE modelling procedure of misaligned clad pipeline are introduced. Sections 4 and 5 present the parametric studies of misaligned clad pipeline containing a surface crack located in weld centre line (WCL) (Souza et al., 2016; Yi et al., 2012a, b; Zhang et al., 2013a, b) and fusion line (FL) (Macdonald and Cheaitani, 2010), respectively. The comparison of fracture assessment obtained by BS7910 (2013) and FEM is given in Section 6, and then a strain-based failure assessment curve considering the effect of weld misalignment is proposed.

2. Pipeline geometries and material properties

This section presents the geometrical details and material properties of misaligned clad pipeline.

2.1. Geometrical details

The geometrical configuration of the clad pipeline is illustrated in Fig. 1(a). The outer diameter (D) and the total thickness (t) of the pipeline are 362.8 mm and 20.9 mm, respectively, and the thickness of the CRA layer is 3 mm. In this study, a canoe shape surface crack located in WCL and FL, respectively, is considered, where a is the crack depth and s is half the crack length. A crack in FL is assumed to be located at the interface between the weld metal and the outer pipe, and the narrow heated affected zone (HAZ) is not explicitly considered herein (Kim and Schwalbe, 2001). Two types of centreline offset weld misalignment (e), misalignment with equal diameters (Fig. 1(b)) and misalignment with unequal diameters (Fig. 1(c)) (API 579-1/ASME FFS-1, 2007), are considered. Due to a fabrication tolerance $e/t = 0.15$ being frequently used in fabrication standards for offshore structures (Lotsberg, 1998,

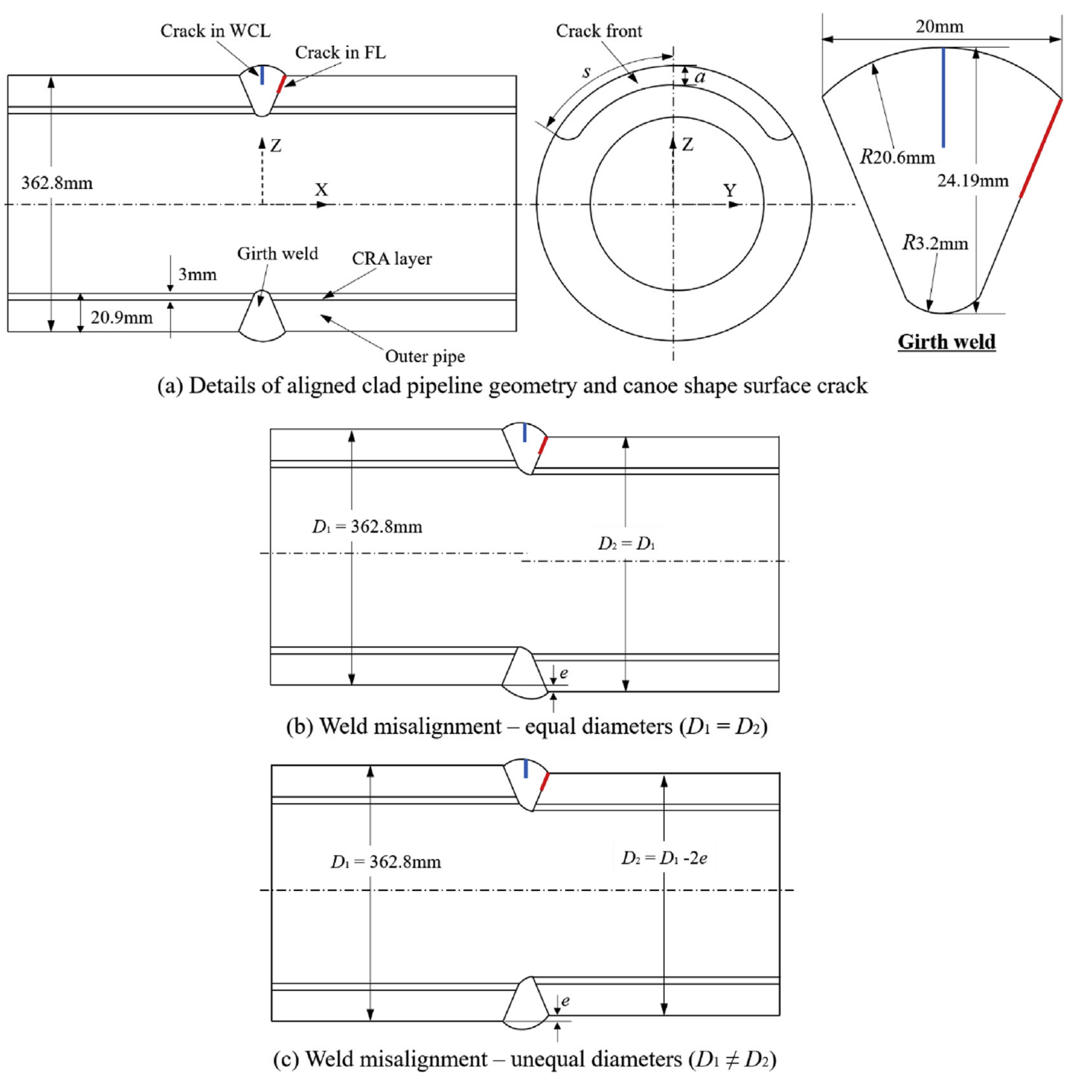

Fig. 1. Geometry of misaligned clad pipeline containing a canoe shape surface crack in WCL (blue line) and FL (red line): (a) Details of aligned pipeline geometry; (b) Cracked pipeline with centreline offset misalignment – equal diameters (API 579-1/ASME FFS-1, 2007); (c) Cracked pipeline with centreline offset misalignment – unequal diameters (API 579-1/ASME FFS-1, 2007). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).