Journal of Loss Prevention in the Process Industries 38 (2015) 67–78

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

Plastic buckling, wrinkling and collapse behaviour of dented X80 steel line pipes under axial compression

M. Zeinoddini [a], M. Ezzati [a, *], G.A.R. Parke [b]

[a] Department of Civil Engineering, K.N. Toosi University of Technology, Tehran, Iran
[b] Department of Civil and Environmental Engineering, Guildford, Surrey, UK

ARTICLE INFO

Article history:
Received 23 February 2015
Received in revised form
22 June 2015
Accepted 5 September 2015
Available online 7 September 2015

Keywords:
Experimental study
Numerical simulation
Steel tubes
Dent
High strength steel monotonic axial compression

ABSTRACT

High strength steel pipes have found increasing applications in deep high pressure offshore oil/gas lines. Damages in the form of dent are among common causes of pipeline failure. Indentation, plastic buckling and residual strength of dented normal grade steel pipes under bending, axial and combined loading have previously been addressed by a number of researchers. The plastic buckling and collapse of dented high grades steel line pipes, however, have received less previous attentions.

In the current study an experimental model testing was used to evaluate the residual strength of dented X80 steel pipes under monotonic axial compression. The tubular specimens were first laterally dented by an indentor while resting on a saddle shape support. The specimens were then examined under axial compression to study the dent effects on their collapse behaviour. Numerical simulations were also used to analyse the effect of the indentor ratio, shape and alignment on the residual strength of dented steel tubes under monotonic axial compression. The results from the current study on high strength steels were also compared with semi-empirical equations available in the literature for low strength steels. It was found that these equations provide reasonable predictions for the axial residual capacity of the high strength steel pipes when the dent depths are small. With deep dents, however, they considerably underestimate the axial residual capacity of the high strength steel pipes.

1. Introduction

Tubular steel sections are widely used in construction industry, mechanical parts, power plants, petrochemical plants, space frames, pipelines, flow lines, risers, casings and other onshore and offshore applications. In particular, they are a key element in oil and gas industry and are used in exploration, drilling, production, and transmission. The focus of the current paper is on carbon steel offshore oil/gas pipelines but, the results may be applicable in inelastic assessment of tubular structures in general.

Offshore pipelines are relatively large scale infrastructures installed in hostile environments. They are usually laid unburied, so they might become disposed to heavy accidental transverse loads. The transverse loads may be produced by impacts from external objects and other causes during transportation, installation and service life of the line such as those caused by collisions from trawl gears, anchors or other dropped objects. Lateral mechanical damages could occur also in a buried pipeline by impacts from earth excavation equipment or rock dumping and in offshore platforms by ship impacts.

Common causes of service failures in steel gas transmission pipelines in Europe with their percentage of occurrence are given in Table 1. The table indicates on mechanical damages (external interference) as the major cause of failure (Allouti et al., 2012). Mechanical damages can themselves be classified into gouges and dents. Damages in the form of dents are one of the most common causes of pipeline failures (Kyriakides and Corona, 2007).

Presence of a dent reduces the collapse capacity and the local buckling strength of the pipe, and can be the initiators of propagating buckles. In addition, for gas lines under high internal pressure, dents, sometimes accompanied by gouges, are often the prelude to burst failures. Once a defect is detected, the operator must decide on the integrity of the structure. Defect assessment in pipeline is made using different tools according to defect types and failure modes. Offshore repairs are generally complicated and very costly. Thus, the ability to assess the integrity of the dented pipe

* Corresponding author.
E-mail addresses: Zeinoddini@Kntu.ac.ir (M. Zeinoddini), Mezzati@sina.Kntu.ac.ir (M. Ezzati), g.parke@surrey.ac.uk (G.A.R. Parke).

http://dx.doi.org/10.1016/j.jlp.2015.09.002
0950-4230/

Nomenclature

E	Young modulus.
S_y	yield stress of material.
S_u	ultimate stress of material.
D	pipe outer diameter.
t	pipe wall thickness.
X	dent depth.
d	indentor diameter.
F_L	limit axial load.
ε_L	axial strain at limit load.
A_0	cross section area of the pipe.
$F_{char.-anal.}$	characteristic axial compressive capacity for a steel tube from semi-analytical equations.
$F_{char.-test}$	characteristic axial compressive capacity for a steel tube from tests.
$F_{char.-num.}$	characteristic axial compressive capacity for a steel tube from numerical simulation.
$f_{char.}$	characteristic axial compressive stress for a steel tube.
λ_d	reduced slenderness of the dented steel tube: $\lambda_d = \sqrt{\frac{\varepsilon_C}{\varepsilon_M}} \cdot \lambda_0$, $\varepsilon_C = \exp\left(-0.08\frac{X}{t}\right)$, $\varepsilon_M = \exp\left(-0.06\frac{X}{t}\right)$
λ_0	reduced slenderness of an intact steel tube.

analytically is very important (Kyriakides and Corona, 2007).

A dent in a tubular element is defined as a permanent plastic deformation of the circular cross-section of the pipe. It can be categorised according to its extent and geometry, as listed below (Wang and Smith, 1982):

- Smooth dent: is a dent that causes a smooth change in curvature of the pipe wall,
- Kinked dent: is a dent that causes an abrupt change in curvature of the pipe wall,
- Plain dent: is a smooth dent that contains no wall thickness reduction,
- Unconstrained dent: is a dent that is free to rebound elastically when the indentor is removed,
- Constrained dent: is a dent that is not free to rebound because the indentor is not removed.

Dent depth (X) is defined as the maximum reduction in the diameter of the tubular section compared to the original diameter (Fig. 1). It is the most significant factor affecting the burst strength and the fatigue strength of a plain dent (Cosham and Hopkins, 2004). Denting can be divided into two elastic and plastic parts. When the indentor is removed the dent will 'spring back' to some degrees. The depth of a dent in a pipeline changes as the internal pressure changes; a dent rebounds under increasing internal pressure.

Residual capacity of defected steel tubular members has already been addressed by other researchers (Limam et al., 2012; Chen et al., 2014). The collapse of mild steel pipes containing plain or gouged dents was studied under internal pressure and bending. They demonstrated that the presence of dent in steel tubular members reduces the bending capacity (Limam et al., 2012). The behaviour of dented pipes was also studies under external pressure (Park and Kyriakides, 1996), internal pressure (Allouti et al., 2012), cyclic internal pressure (Pinheiro et al., 2014), and monotonic/cyclic axial loading (Azadeh and Taheri, 2014; Zeinoddini et al., 2014). However, studies involving the effect of local geometrical imperfections, such as non-uniformity in thickness, local indentations, dents, cracks, non-circularity and non-cylindricality on the buckling of cylindrical shells appear to be limited in number (Shen and Li, 2002).

Effects of multiple large diamond shaped dimples on the buckling behaviour and load carrying capacity of cylindrical shells under axial compression were experimentally investigated by Krishnakumar and Forster (Krishnakumar and Foster, 1991). Hambly and Calladine (Hambly and Calladine, 1996) studied dented drinks cans ($R/t = 350$) under eccentric axial compression. They reported that the nominal stress level in the dent region on buckling was 0.24 times of classical buckling stress. Prabu et al. (Prabu et al., 2010) used finite element modelling to study the dent effects on buckling of short carbon steel cylindrical shell. They showed that the buckling or collapse strength of dented cylindrical shells decreases with increase in both diameter and depth of the dent.

High strength steel line pipes have found increasing applications in the offshore oil/gas industry in particular for high pressure deep water gas lines. This is because the ever increasing demand for hydrocarbon products requires construction of long high pressure oil/gas transmission lines. In order to meet the demand requirements and to improve the transportation efficiency, utilising high-strength steel grades for oil/gas line pipes has been widely accepted by the industry. Promoting the steel grade is a very convenient solution, in particular for long and deep offshore pipelines, to reduce the costs of the line construction and the product transportation. The use of higher strength steels avoids designs for pipes of large wall thickness that would be otherwise needed (Hillenbrand et al., 2002).

Line pipes of API grade X80 have already been put into practical use, and line pipes of API grade X100 and higher are now in demand. Generally, the fracture toughness required for pipeline safety increases with increases in the strength. However, as the strength

Table 1
Common causes of service failures in steel gas transmission pipelines in Europe (Allouti et al., 2012).

External interference (%)	Construction defects or material failure (%)	Corrosion (%)	Ground movement (%)	Hot-tap made by error (%)	Other or unknown (%)
49.6	16.5	15.3	7.3	4.6	6.7

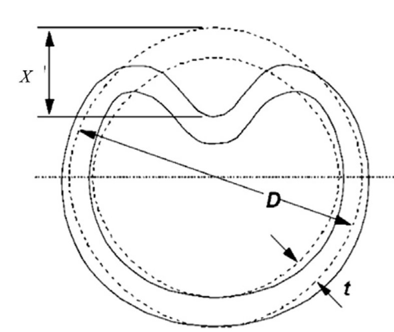

Fig. 1. Definition of the dent depth (Prabu et al., 2010).