International Journal of Fatigue 68 (2014) 38–47

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Fatigue life assessment of damaged pipelines under cyclic internal pressure: Pipelines with longitudinal and transverse plain dents

B. Pinheiro [a,*], I. Pasqualino [a], S. Cunha [b]

[a] Subsea Technology Laboratory (LTS), Ocean Engineering Department, COPPE/Federal University of Rio de Janeiro, PO Box 68508, Cidade Universitária, CEP 21941-909 Rio de Janeiro/RJ, Brazil

[b] Petrobras/Transpetro, Av. Pres. Vargas 328, 7th Floor, CEP 20091-060 Rio de Janeiro/RJ, Brazil

ARTICLE INFO

Article history:
Received 6 February 2014
Received in revised form 30 May 2014
Accepted 3 June 2014
Available online 12 June 2014

Keywords:
Pipelines
Mechanical damage
Plain dents
Stress concentration factors
High cycle fatigue

ABSTRACT

This ongoing work aims to refine a methodology for fatigue life assessment of dented steel pipelines under cyclic internal pressure. A numerical model is developed to obtain stress concentration factors on dented pipes under internal pressure. A comprehensive parametric study is accomplished and analytical expressions to estimate stress concentration factors for spherical, longitudinal and transverse plain dents as a function of selected geometric parameters are developed. The proposed fatigue assessment methodology is validated from fatigue test results. Here, the analytical expressions are refined to include a more complete dent geometry definition for transverse, longitudinal and short longitudinal dents.

1. Introduction

The high cycle fatigue failure originated from stress concentration is one of the most common failure modes of oil and gas pipelines presenting dent defects [1]. Dents can be introduced during pipe installation or by the impact of excavation equipment or any heavy objects (as anchors), for instance, and may assume different shapes and dimensions, accumulating high levels of plastic strain and residual stresses. During operation, oil and gas pipelines undergo cyclic loadings generated by fluid pressure and temperature changes and also, in the case of offshore pipelines, by the action of waves or subsea streams.

High cycle fatigue becomes a main concern when a steel pipeline is subjected to mechanical damage, as a dent defect, for example. The fatigue life assessment of dented steel pipes can avoid flow interruptions, caused by unnecessary repairs, or leaks, which may lead to environmental damage, societal consequences and financial loss. This assessment should take into account the stress concentration in the damaged section.

Stress concentration factors (SCFs) have been the main focus of previous studies on the fatigue behavior of dented steel pipelines [2–9]. It was found that stress concentration factors in dented sections are mainly function of pipe and dent dimensions, material properties and boundary conditions [2–8]. These previous studies also involved the proposal of methods to assess the fatigue life of dented pipelines based on empirical formulations and numerical simulations [5–8]. Some of these methods have been discussed by Cosham and Hopkins [10]. Numerical models based on the finite element (FE) method, for instance, can precisely evaluate SCFs for even complex structures, but it requires an experienced professional and several hours of computer processing. Direct formulations derived from FE results can be of practical application to obtain the desired SCFs and carry out a fatigue analysis based on a theoretical approach.

The present work is devoted to refine the methodology for fatigue life assessment of dented steel pipelines earlier presented by Cunha et al. in [11]. This methodology is based on current high cycle fatigue theory and employs stress concentration factors to modify standard S–N curves of steel components under cyclic loadings.

In a former work [12], the strain behavior of small-scale steel pipe samples during denting and cyclic internal pressure is evaluated with the aid of experimental tests. Then, a nonlinear finite element (FE) model is developed to obtain stress concentration factors resulting from spherical plain dents on steel pipes under internal pressure. This FE model is validated according to strain history responses obtained experimentally and used in an extensive parametric study under different pipe and dent dimensions,

* Corresponding author. Tel.: +55 21 3938 7794x215; fax: +55 21 3938 7790.
E-mail addresses: bianca@lts.coppe.ufrj.br, biancapinheiro@hotmail.com (B. Pinheiro).

http://dx.doi.org/10.1016/j.ijfatigue.2014.06.003
0142-1123/

Nomenclature

d	dent depth (mm)
k_a	surface condition modification factor
l	dent length
q	notch sensitivity factor
t	pipe wall thickness (mm)
w	dent width
B	non-dimensional dent geometric parameter
D	pipe external diameter (mm)
K_f	fatigue stress concentration factor
K_t	theoretical (or geometric) stress concentration factor
N	number of stress cycles to failure
S_e	endurance limit of a real component (MPa)
S'_e	endurance limit of a standard test sample (MPa)
S_u	ultimate tensile strength (MPa)
S_y	yield strength (MPa)
$\bar{\sigma}$	von Mises equivalent stress (MPa)
σ_a	alternating stress (MPa)
σ_f	true stress of failure in a tension test (MPa)
σ_m	mean (or static) stress (MPa)
σ_{max}	peak (maximum) stress (MPa)
σ_{nom}	nominal stress (MPa)

providing data for the development of analytical expressions to estimate SCFs of spherical dents as a function of relevant geometric parameters. The validity of the SCFs obtained by these expressions is then verified according to small-scale fatigue test results of steel pipe samples with spherical dents under cyclic internal pressure. In a subsequent article [11], a geometrical classification of dents is introduced, simple expressions for SCFs of spherical, transverse, longitudinal and short longitudinal dents are presented and a fatigue assessment methodology is developed and compared to full-scale test results from the literature.

Here, stress concentration factors associated with longitudinal and transverse plain dents are addressed. The previously developed FE model [11–14] is adapted to provide more accurate stress concentration factors for these dent shapes and several finite element analyses are carried out in a comprehensive parametric study with different pipe and dent dimensions. The FE analyses comprise an elastic–plastic simulation of the denting process followed by an elastic determination of the stress concentration factor. Then, analytical expressions to estimate SCFs for these two dent shapes as a function of relevant geometric parameters are developed with the aid of the Buckingham's Π theorem [15]. Finally, the proposed fatigue assessment methodology [11] is refined with the addition of these more accurate expressions.

The proposed methodology [11] can then be used to assess the fatigue life of steel pipelines with dent defects of different shapes and dimensions, based on the current high cycle fatigue theory and employing SCFs provided by simple expressions. The correlation to results of full-scale fatigue tests available in the literature [5,6] validates it and shows that the stress concentration factors given by the proposed expressions are accurate. Further full-scale fatigue test results can be found in the literature and their correlation to the proposed fatigue assessment methodology will be considered in a future work.

2. Numerical model

A numerical procedure based on the finite element method was adopted to estimate stress concentration factors induced by plain dents on steel pipes under internal pressure [12–14]. It was developed using the mainframe ABAQUS [16] and comprises a nonlinear three-dimensional shell type model (finite element mesh) representing the steel pipe and an analytical rigid surface to reproduce the denting tool.

Based on experimental and numerical evidences, dented steel pipes under cyclic internal pressure might be considered to deform elastically after the first cycle (rerounding) if the maximum internal pressure is not exceeded [2,7,9,12,13]. In addition, although stress concentration factors (SCFs) can be affected by residual stresses, preliminary analyses have shown that their influence is not significant. Therefore, for subsequent pressure cycles, SCFs may be obtained from simple linear elastic analyses and residual stresses could be neglected. SCFs can then be related only to dent geometric parameters within the elastic regime.

Consequently, the numerical model comprised a nonlinear elastic–plastic analysis, to simulate the denting process and generate the deformed pipe geometry, and a subsequent elastic analysis, to determine the stress concentration factor. The adopted methodology filters strain hardening effects from SCFs. Other parameter that was disregarded is the stress stiffening generated by the internal pressure, which can affect the resulting SCFs.

The elastic–plastic analysis comprised the load steps of denting and removal of the denting tool (spring back). As a result of this analysis, the deformed pipe geometry was then assumed as the initial configuration for the elastic analysis. The elastic analysis comprised a single load step, corresponding to a small internal pressure, sufficient to generate the elastic response and provide the stress concentration factor.

The finite element (FE) model was initially developed to provide SCFs for spherical dents [12–14], as shown in Fig. 1. Afterwards, it was modified to generate stress concentration factors associated with longitudinal and transverse plain dents [11]. With this purpose, a cylindrical denting tool is considered, placed parallel or normal to the pipe longitudinal axis in the case of longitudinal or transverse dents, as shown in Figs. 2 and 3, respectively.

2.1. Model geometry

The FE model is comprised of the pipe surface and the denting tool. The pipe is defined by a middle surface diameter (D) of 73 mm and a wall thickness (t) of 3.05 mm, corresponding to a D/t ratio of about 24. These dimensions characterize the fatigue test samples carried out (Section 4), but they can be varied in order to perform a parametric study (Section 3). According to preliminary FE analyses for longitudinal and transverse dents, it was found that the original pipe longitudinal length (10D) [12–14] should be increased to minimize any interaction between the stress field in the dented region and the pipe edges. The pipe longitudinal length was then set to 12D, which was found adequate to minimize edge effects to these new dent shapes. To reduce the computational time in numerical analyses, a quarter-symmetry model was used, considering symmetries in longitudinal (1–2) and transverse (2–3) planes, according to Figs. 1–3.

2.2. Constitutive model

The material properties adopted in the FE model were obtained through uniaxial tension tests on specimens machined from SAE/AISI 1020 grade steel pipe sections used to produce the fatigue test