Available online at www.sciencedirect.com

ScienceDirect

Engineering Fracture Mechanics 75 (2008) 2352–2366

Engineering Fracture Mechanics

www.elsevier.com/locate/engfracmech

Ultimate fracture capacity of pressurised pipes with defects – Comparisons of large scale testing and numerical simulations

E. Berg [a,*], E. Østby [c], C. Thaulow [b], B. Skallerud [a]

[a] *Department of Structural Engineering, Norwegian University of Science and Technology, N-7491 Trondheim, Norway*
[b] *Department of Engineering Design and Materials, Norwegian University of Science and Technology, N-7491 Trondheim, Norway*
[c] *SINTEF Materials and Chemistry, 7491 Trondheim, Norway*

Received 24 April 2007; received in revised form 12 August 2007; accepted 4 September 2007
Available online 18 September 2007

Abstract

In this paper results from large scale 4-point bending tests of pipe-segments are compared with numerical analyses using LINK$_{pipe}$. The experiments were carried out as a part of the joint industry project Fracture Control – Offshore Pipelines. The comparisons between large scale testing of pipelines and numerical analyses also address the effect of biaxial loading on the strain capacity. The defect is positioned on the tension side of the pipe when applying the load. A parametric study on changing the nominal wall thickness of the pipe is carried out. Due to variation in the yield stress, a parametric study to see the effect of this variation was also performed. The results demonstrate that ductile crack growth and biaxial loading are important elements in fracture assessment procedures for pipelines.

Keywords: Fracture mechanics; Line-spring; Biaxial loading; Ductile crack growth; Large scale testing

1. Introduction

Surface cracks due to welding defects, corrosion, etc., may occur in pipelines. Offshore pipelines usually consist of many kilometres of girth welds, thus the possibilities of defects being present must be taken into account during design. Further, there is an emerging trend that pipelines may be subject to larger deformation both during installation and operation. For installation scenarios the reeling method is well known, yielding plastic strains in the pipe up to 3%. But also other installation methods, like, e.g. S-laying, may result in plastic strains. During operation on-bottom snaking, upheaval buckling, landslide and seismic activity can lead to significant deformations in the pipe. For these latter cases this will usually occur while the pipe is pressurised, and there is a biaxial loading in the pipe wall. Current fracture assessment procedures are not developed to

---

[*] Corresponding author.
E-mail address: espen.berg@ntnu.no (E. Berg).

0013-7944/$ - see front matter © 2007 Published by Elsevier Ltd.
doi:10.1016/j.engfracmech.2007.09.004

handle cases where global plastic deformations occur. Thus, there has been a great interest in developing a fracture assessment procedure to address such loading scenarios in the recent years (see, e.g. [1–6]), often referred to as strain-based approaches. A specific issue of concern is the effect biaxial loading. For pipes subjected to a global bending moment, two competing failure modes are acting at the same time. The first failure mode is fracture where the crack grows through the thickness, and the second failure mode is a structural failure, e.g. local buckling. For the local buckling failure mode the biaxial loading has been shown to have a beneficial effect on the deformation capacity [7]. However, numerical studies [8–11] have pointed in the direction that the biaxial loading may increase the crack driving force as a function of the applied strain, an effect not accounted for in existing assessment procedures. Thus, it could be detrimental for the deformation capacity of pressurised pipes with defects. Østby and Hellesvik [12] have recently provided experimental large scale verification of the detrimental effect of biaxial loading on the strain capacity of pipes. These results clearly demonstrate the need for assessment procedures capable of handling this effect.

In fracture assessments of pipelines, the wall-stresses are mainly of membrane type (see [13]). This will lower the constraint level in the near crack-tip stress field, thus increasing the fracture toughness. Use of tearing curve based on a high-constrained fracture specimen can lead to very conservative decisions. A methodology to account for reduced constraint using a single edge notched tensile specimen (SENT) for fracture assessment was proposed by Nyhus et al. [15] and demonstrated by Berg et al. [18]. To account for surface cracks, line-springs are used herein [19–23,10,24]. The present study addresses comparisons between the shell- and line-spring model and the results from the large scale testing presented in [12]. The software LINK$_{\text{pipe}}$ is employed (see [25] for details). Ductile crack growth in thickness and circumferential direction is accounted for in the numerical analyses in this study by employing the crack growth resistance curve (see Section 5). The effects of changing the nominal wall thickness and yield stress are also studied and presented herein. Some of the experiments are also performed with biaxial loading by means of internal pressure in addition to global bending. All of the experiments are performed with an external surface crack, thus pressure on the crack faces is not relevant.

2. Theory

2.1. Line-spring

A surface flaw in a finite element model consisting of shell elements can be accounted for by employing line-spring elements. In the elastic line-spring formulation, the generalised displacements and the internal forces are related through the compliance matrix. This matrix is determined from single edge notched (SEN) specimens using the energy/compliance proposed by Rice and Levy [20]. The elastic–plastic line-spring element is based on a set of convex yield surfaces, $\Phi\{Q_i; a; t; \sigma_y(\varepsilon^{\mathrm{p}})\}$, where Q_i are the generalised forces in the line-spring element, a is the crack depth, t is the wall thickness, and $\sigma_y(\varepsilon^{\mathrm{p}})$ is the current uniaxial yield stress at an equivalent plastic strain of ε^{p} according to the material's stress–strain curve. The yield surfaces for the line-spring element use the tabulated values for different crack depth to thickness ratios published by Lee and Parks [26]. Simulations of additional crack ratios were carried out by the authors to refine the transition between the tabulated crack ratios provided in the literature. Further details of the theory and implementation of the software LINK$_{\text{pipe}}$ are provided by Skallerud et al. [23,25].

Ductile crack growth is implemented in the line-spring element as an incremental formulation. The crack propagates quasi-statically through the thickness based on the crack growth resistance curve given as input to the analysis. This crack growth resistance curve can be treated as a material parameter for a given constraint level. The updated crack dimensions at the end of a load increment is expressed as $a^{(i+1)} = a^{(i)} + \Delta a^{(i)}$ and $c^{(i+1)} = c^{(i)} + \Delta c^{(i)}$. The crack growth resistance curve can be obtained from fracture mechanic experiments or from a damage mechanic numerical analysis (e.g. Gurson–Tvergaard–Needleman model). The crack growth resistance curve used is of the form presented in Fig. 7.

Crack growth in circumferential direction is accounted for and implemented as shown in Fig. 1a, and presented in detail by Berg et al. [18]. A set of 3D-analyses were performed by Sandvik et al. [27], and the circumferential crack growth was obtained in these analyses. An interpolation between these 3D-results was performed to make a general quantification of the circumferential crack growth (see Fig. 1b).