International Journal of Fatigue 87 (2016) 279–287

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Stress intensity factors for fatigue analysis of weld toe cracks in a girth-welded pipe

Hsin Jen Hoh, John Hock Lye Pang *, Kin Shun Tsang

Maritime Institute, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore
School of Mechanical & Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

ARTICLE INFO

Article history:
Received 20 October 2015
Received in revised form 27 January 2016
Accepted 1 February 2016
Available online 8 February 2016

Keywords:
Circumferential weld
Fatigue crack
Finite element
Stress intensity factors
Weld toe magnification factor

ABSTRACT

This paper addresses the lack of three-dimensional stress intensity factor solutions for small to large surface cracks located at the weld toe region of welded pipes. A methodology was developed to model and calculate the stress intensity factors and weld toe magnification factors for semi-elliptical surface cracks in a circumferentially welded pipe. Three-dimensional finite element models were developed for a wide range of surface crack geometries. The stress intensity factors for surface cracks in a plain pipe were benchmarked with reported results and showed good agreement to within 2.6%. Stress intensity factors and weld toe magnification factors solutions were determined for weld toe surface cracks located at a circumferentially welded pipe. The weld toe semi-elliptical surface cracks geometries vary from small crack depth-to-thickness (a/t) ratios of 0.05 to large crack depth-to-thickness (a/t) ratio of 0.5. Three semi-elliptical surface crack shape aspect ratios (a/c) were modelled for values of 1.0, 0.5 and 0.25. The stress intensity factor and weld toe magnification factors solutions are reported in this paper for a wide range of semi-elliptical surface crack geometries with crack depth-to-thickness ratios (a/t) from 0.05 to 0.5 and crack shape aspect ratios (a/c) from 0.25 to 1.0 subject to pipe wall tension and bending loading. The stress intensity factor and weld toe magnification factors solutions are used for fatigue crack growth prediction assessment of weld toe surface cracks propagating in a circumferentially welded pipe.

1. Introduction

Welded pipes and risers are important structural elements employed in the oil and gas industry to interconnect subsea oil and gas pipelines to offshore production platforms. These structures are carefully designed with high fatigue endurance to withstand the dynamic offshore wave and current loadings in service. This is because in-service fatigue crack growth damage in welded pipe and risers is a major concern that can lead to dangerous leaks or catastrophic pipeline containment failure, incurring great economic loss and adverse environmental pollution impact. The fatigue life of these pipelines and risers, fabricated by girth welding pipe segments, are prone to fatigue failure by crack propagation of multiple weld toe cracks that are notoriously found at the weld toe region of girth welds and welded structures.

One useful approach to predict the fatigue life of such welded structures is based on linear elastic fracture mechanics, which considers inherent cracks (of depth, a) that grow at rates (da/dN) corresponding to the applied stress intensity factor range (ΔK) subject to cyclic stresses. The fatigue crack growth analysis employs stress intensity factor (SIF) solutions for geometries such as weld toe cracks in T-butt joints [1] and tubular joints [2], surface-cracked plates [3], as well as cracked pipes without welds [4], which were developed using finite element modelling. The SIF solutions are integrated into fitness-for-service assessments procedure for crack-like flaw assessments in the BS 7910:2013 [5] and API 579-1/FFS-1 2007 [6] codes. The finite element method has also been used to study mixed mode fracture of pipes [7,8]. Meanwhile, the boundary element method has been used to study the behaviour of cruciform welded joints [9]. Alternatively, substitute geometries can be used to determine the SIFs if the stress distribution across the wall is known [10], while the weight function approach has been used to study the thermal SIFs in cracked pipes [11]. Circumferential periodic cracked pipes and shells were studied using an analytical method based on the conservation law and bending theory [12].

However, the corresponding SIF solutions for semi-elliptical, weld toe cracks in circumferentially welded pipes are not available. The motivations of this work are to develop a three-dimensional (3D) finite element modelling methodology for determining SIF solutions for weld toe cracks in circumferentially welded pipes.

* Corresponding author. Tel.: +65 6790 5514.
E-mail address: mhlpang@ntu.edu.sg (J.H.L. Pang).

http://dx.doi.org/10.1016/j.ijfatigue.2016.02.002
0142-1123/

The SIF solutions will be reported for a range of small to large surface cracks at weld toe regions as they are needed for fatigue crack growth assessments of circumferentially welded pipes in fitness-for-service assessment codes [5,6] where such SIF solutions are currently not available. This paper will provide new data for SIF and weld toe magnification factor (M_k-factors) solutions for semi-elliptical surface cracks located at the weld toe of a circumferentially welded pipe. The SIF and M_k-factor solutions will be reported for crack depth-to-thickness ratios (a/t) from 0.05 to 0.5 with crack shape aspect ratios (a/c) from 0.25 to 1 subject to pipe tension and bending loadings.

2. Finite element modelling of surface cracks in a plain pipe

2.1. Details of plain pipe geometry

The plain pipe geometry considered (Fig. 1) can be described by its internal radius R_i and wall thickness t, while the crack is of depth a and width c. The crack geometry was transformed from a cracked flat plate deformed to form a cracked cylinder [4], with the crack front given by equations:

$$x = (R_i + t - a\sin\phi)\sin\frac{c\cos\phi}{R_i + t}$$
$$y = (R_i + t - a\sin\phi)\cos\frac{c\cos\phi}{R_i + t} \quad (1)$$

where ϕ represents the angle of the crack tip along the crack front, according to the pre-transformed crack in the flat plate.

A typical pipeline geometry [13] was used as an example, with dimensions $R_i = 160.5$ mm, $t = 20.9$ mm. To study the effect of the weld geometry, the material properties were assumed homogeneous, with $E = 210$ GPa and $\nu = 0.3$.

2.2. Modelling methodology

Using symmetry, a half-pipe geometry was modelled along the y-axis indicated in Fig. 1. The full 3D model of the pipe is shown in Fig. 2. It typically consists of about 120,000 3D isoparametric hexahedral elements. The boundary conditions and loading conditions in tension and bending are shown in Fig. 3a and b, respectively.

The loading conditions were achieved by fixing one end of the pipe and applying a displacement load at the free end. A constant displacement load δ can be related to the tensile stress σ by

$$\sigma = \frac{E\delta}{2L} \quad (2)$$

where E is the Young's modulus and L is half the length of the pipe. For bending, a linearly distributed displacement load is applied across the free end of the pipe such that the maximum tensile displacement (δ) is at the top of the pipe while the maximum compressive load ($-\delta$) is at the bottom.

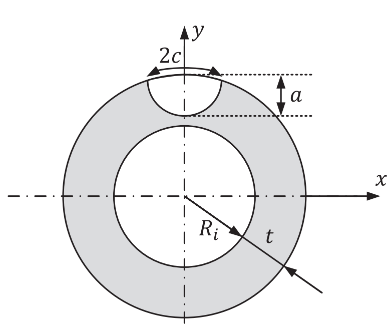

Fig. 1. Plain pipe with circumferential external surface crack.

The pre-processing stage was automated by scripting to generate the half-pipe using geometric data and mesh parameters as input. The scripting also deals with the tedious partitioning of the pipe to achieve a focused mesh under different crack depths relative to the pipe. The partitioned pipe allowed a focused mesh of spider-web configuration along the semi-elliptical crack front (Fig. 2). The spider-web mesh configuration is made up of concentric rings that give more accurate evaluation of the J-integral contour. The mesh has coarser quadrilateral rings remote from the crack tip that gradually decrease in size as the crack tip is approached, before finally degenerating into fine triangular elements at the crack tip. The 3D crack front mesh designs were generated for a range of a/t and a/c values. As cracks with narrow aspect ratios (a/c) and small sizes (a/t) were considered, further partitions were automated as required to improve meshing as shown in Fig. 4 from larger surface cracks (Fig. 4a–c) to small surface cracks (Fig. 4d–f).

The finite element mesh is composed of 20-noded isoparametric hexahedral elements. At the crack front, a focused mesh was used, where the hexahedral elements were collapsed into singular wedge elements (Fig. 2). The mid-side nodes located perpendicular to the crack front were not shifted to a quarter-point location because a sufficiently fine mesh (crack tip element is 2% of the crack depth) was employed [1].

Post-processing requires handling of the J-integral, which refers to the path-independent contour integral around a crack used to determine the strain energy release rate. In three-dimensions the J-integral is given by

$$J = \lim_{\Gamma\to 0}\int_A \lambda(s)\mathbf{n}\cdot\left(W\mathbf{I} - \boldsymbol{\sigma}\cdot\frac{\partial \boldsymbol{u}}{\partial \boldsymbol{x}}\right)\cdot\mathbf{q}\,dA \quad (3)$$

where $\lambda(s)$ is the virtual crack advance (of local direction $\mathbf{q}$) at point s along the crack front; dA is a surface element with outward normal $\mathbf{n}$; W is the elastic strain energy; $\boldsymbol{\sigma}$, $\boldsymbol{u}$, $\boldsymbol{x}$ represent the surface traction, displacement and coordinate directions, respectively.

By nature of the approximation used in the finite element formulation, the J-integral evaluations in different contours may differ. Hence, the average J-integral value of the second to fifth contours was used. For linear elastic material response, the SIFs can be derived from the J-integral averages, assuming plane strain conditions throughout the crack front, using the relation

$$K_I = \sqrt{\frac{JE}{1-\nu^2}} \quad (4)$$

where J refers to the average J-integral values, E is the Young's modulus and ν is the Poisson's ratio.

2.3. Stress intensity factors for large surface cracks in plain pipe

The resulting SIF values obtained for an offshore pipe with an external circumferential weld toe crack subject to tension or bending, for a/t of 0.05–0.5 and a/c of 0.25–1.0 were benchmarked to previous work by Bergman [4]. The thickness of the pipe, t was 20.9 mm, while the length of the pipe ($2L$) was ten times the thickness. The shape factors at the deepest point, Y_a ($\phi = 90^\circ$) and surface, Y_c ($\phi = 0^\circ$) are obtained by

$$Y_a = \frac{K_a}{\sigma\sqrt{\pi a}} \quad (5a)$$

$$Y_c = \frac{K_c}{\sigma\sqrt{\pi a}} \quad (5b)$$

where σ is the applied stress in tension or the maximum stress in bending, both obtained from (2), while a is the crack depth (Fig. 1).