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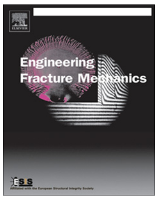

Analytical model of elastic fracture toughness for steel pipes with internal cracks

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ABSTRACT

Corrosion or manufacture defects can cause internal cracks in steel pipes. For ductile materials, the crack front can yield before the stress intensity reaches its fracture toughness. The yielding of the crack front could ease the stress concentration at the crack front. Therefore, to predict the failure of cracked steel pipes using linear elastic fracture mechanics it is necessary to quantify the part of fracture toughness that withstands the elastic stress field, namely, elastic fracture toughness. This paper intends to propose an analytical model of the elastic fracture toughness for steel pipes with internal surface cracks.

1. Introduction

Pipes are widely used to transport gas or liquid in infrastructure and industries, e.g., water, oil/gas, carbon dioxide, etc. These pipes are made of various materials based on different needs amongst which steel is very commonly used. For steel material, there are a number of classes or grades according to the carbon content with different mechanical properties. Most of steel materials exhibit ductile behaviour, demonstrated by yielding of the material. The yielding behaviour allows the steel pipes undergo significant amount of deformation before the collapse which to some extent prevents catastrophic failures. When pipes collapse, however they fail, it can be socially, economically and environmentally devastating, causing, e.g., enormous disruption of daily life, massive costs of reinstatement, widespread flooding and subsequent pollution, and so on.

Like in many other structures, it is inevitable to have defects or cracks in steel pipes. The defects are normally produced during manufacturing process and the cracks are mainly induced by material deterioration, e.g., corrosion. Surface cracks are perhaps the most common form [1] and usually treated as semi-elliptical shape [2,3]. The schematic and geometry of the surface crack in a pipe is shown in Fig. 1. Due to the presence of surface cracks, the stress in a pipe will concentrate around those cracks, known as stress singularity, which is one of main causes for pipe collapse. For brittle materials, e.g., cast iron, stress is developed around cracks elastically and the stress intensity factor can be determined from elastic fracture mechanics to represent the singularised stress. When the stress intensity factor reaches a critical limit, known as fracture toughness, K_{IC}, any extra load will cause the failure of the structure.

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Nomenclature

a	depth of surface semi-elliptical crack
c	half-length of surface semi-elliptical crack
$F_1, F_2, \ldots, F_6$	coefficients used to fit influence coefficients G_0^D and G_1^D
G_0, G_1, G_2, G_3	influence coefficients subjected to constant, linear, quadratic and cubic stress distributions on the surface crack
G_0^S, G_1^S	influence coefficients for the surface point subjected to constant and linear stress distributions on the surface crack
G_0^D, G_1^D	influence coefficients for the deepest point subjected to constant and linear stress distributions on the surface crack
$H_1, H_2, \ldots, H_6$	coefficients used to fit influence coefficients G_0^S and G_1^S
K_I	stress intensity factor for opening mode fracture
K_{IC}	fracture toughness for opening mode fracture
K'_{IC}	elastic fracture toughness for opening mode fracture
l	length of a pipe
m	weight function
$m_S,\ m_D$	weight functions for surface point and deepest point respectively
K_r	coefficient measuring fracture failure
K_{rc}	critical limit of K_r
L_r	coefficient measuring loss of strength
$L_r^{\max}$	maximum value of L_r
P	applied load/pressure of cracked pipes
P_L	plastic limit load/pressure of cracked pipes
Q	elliptical integral of the second kind
r	radial distance from the crack tip
R	inner radius of a pipe
t	thickness of the wall of a pipe
x	coordinate along the crack depth
$\overline{\sigma}$	uniaxial flow stress
σ_y	uniaxial lower yield stress
ϕ	position angle along the crack front

When a structure is made of ductile materials, the crack front/tip can yield before the stress intensity factors reaches K_{IC}. The yielding of the crack front could ease the stress concentration. As such, at the critical state of fracture, the maximum stress intensity factor, as represented by fracture toughness K_{IC}, consists of elastic and plastic portions and part of stress singularity (or part of K_{IC}) is endured by the yielding of the crack front/tip. In other words, to be able to use linear elastic fracture mechanics, the plastic portion should be excluded from the fracture toughness K_{IC} of the ductile materials. How much to be deducted depends on the extent of plastic property of the material, e.g., yield stress. Therefore, for predicting the failure of defected/cracked pipes of ductile materials without modelling the plastic development around the crack front, it is necessary to quantify the elastic fracture toughness in K_{IC} if the linear elastic fracture mechanics is to be used.

Considerable research has been carried out on determining the stress intensity factors for pipes with internal surface cracks and most of it focuses on brittle materials [3–6]. Milne et al. [7] developed an assessment framework for integrity of ductile pipes containing defects. In their method, the effects of material yielding at the crack front on pipes are considered in combination with elastic fracture analysis in a failure assessment diagram. Critical points in the diagram have been identified based on test results with respect to both fracture and yielding failure. The fracture toughness can be experimentally determined by ASTM standard testing method [8] or some numerical approaches, e.g., [9]. For plastic pipes, most research employed elastic–plastic finite element analysis to investigate the fracture response (Crack Tip Opening Displacement) of the cracked pipes [10–12]. The elastic–plastic fracture analysis is necessary in modelling crack propagation but can demand more effort on simulation than elastic fracture analysis, including computational time. For thin-walled pipes with internal surface cracks, it is reasonable not to allow any crack propagation through the thickness of the pipe. Therefore, linear elastic fracture mechanics can still be used in assessing the failure of plastic pipes as long as the elastic fracture resistance can be identified and formulated. A comprehensive literature review (see References) suggest that very little research has been undertaken that addresses the plastic fracture capacity of pipes made of ductile materials and almost none in an analytical manner. Given the fact that fracture mechanics has been widely employed to determine stress intensity factors for both brittle and ductile materials, there is a clear need to develop a model for elastic fracture toughness with which the simple failure criterion of linear elastic fracture mechanics could be used in assessing cracked ductile pipes and in the meantime the plastic property of pipe is considered.

This paper proposes an analytical model of elastic fracture toughness for steel pipes with internal surface cracks, as a function of geometric and material parameters, i.e., crack/pipe geometry, fracture toughness and yield stress. Weight func-