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An engineering model for rapid crack propagation along fluid pressurized plastic pipe

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ABSTRACT

The appearance of new pipe materials has revived interest in the modelling of rapid crack propagation (RCP) along fluid-pressurized plastic pipelines. The correlation of results from two International Standard RCP test methods—one full-scale and partially simulating installation and service conditions, the other lab-scale—remains imperfectly understood. There is no standard method for measuring the dynamic fracture toughness of the pipe material, and models relating toughness to pipe fracture pressure have not gained widespread use. This paper demonstrates an adaptable, extendable, analytically transparent model which accounts for all major influences including residual stress in the pipe wall, constraint from surrounding backfill and partial substitution of the pressurizing gas by water.

1. Introduction

Because rapid crack propagation (RCP) failures in plastic pipe are so rare, the régime of standards and test methods which made them so has begun to seem oppressive. The understanding of RCP built up over 25 years of research has been challenged by new materials, processes and observations during the decade since basic research was cut back. This is partly because researchers had not delivered a single, commonly accepted model, sufficiently accessible for users to adopt and develop. The present paper addresses that issue and demonstrates a solution.

RCP along a pipeline is characterized by steady axial crack propagation, at a speed comparable to that of decompression in the pressurizing fluid, above a *critical pressure*—below which there is prompt crack arrest. It was first identified as a distinct problem in steel pipe for gas transmission. As recounted by Leis [1], the role of fracture mechanics in research to avoid RCP changed as steels overtook, and were again overtaken by the operating pressure demands made on them. Thermoplastics suitable for pipe extrusion, however, have a yield strain high enough, and a mode of high-speed crack propagation brittle enough, for LEFM to suffice at the pressures of interest. Early experiments by Shannon and Wells [2] on PVC were developed by Greig [3] into the full scale test method, later to become International Standard ISO 13478, for the tougher polyethylene (PE) materials. Subsequent generations of PE now dominate low-pressure gas and water distribution pipe networks.

The classical, quasi-static LEFM analysis of Irwin and Corten [4] led to a closed-form expression for crack driving force:

$$G \equiv G_0 = \frac{\pi p_0^2 (D-2h)^2 (D-h)}{8E_d h^2} = \frac{\pi}{8}\frac{p_0^2}{E_d} D \frac{(D^*-2)^2(D^*-1)}{D^*} \tag{1}$$

where p_0 is the initial line gauge pressure, D and h are the outside diameter and wall thickness of the pipe, D^* is their ratio D/h and E_d is the tensile modulus of the material at an appropriate time scale. Equating Eq. (1) to the dynamic fracture resistance G_d of the pipe wall material predicts a critical pressure:

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Nomenclature

$\dot{a}$	crack speed
A	cross-sectional area of model beam
A_t	crack opening area within outflow zone length
B_c	crack surface width
c_0	velocity of sound in pressurising gas
c_L	longitudinal wave speed in pipe wall material
c_S	shear wave speed in pipe wall material
C_D	diametral pipe relaxation shrinkage due to residual strain
C_1, C_2	numerical constants
D	outside diameter of pipe
D^*	diameter/thickness of pipe
E	tensile modulus of pipe wall material
g_S	strain energy per unit pipe length
g_K	kinetic energy per unit pipe length
G	crack driving force (energy release rate)
G_d	dynamic fracture resistance
h	thickness of pipe wall
I	second moment of area of model beam
L	axial length of pipe pressurising fluid outflow zone
m	dimensionless pipe flaring modulus
M	mass per unit length of model beam
p_0	initial static gauge pressure in pipe
p_1	gauge pressure at tip of propagating crack in pipe
p	gauge pressure within pipe
p_a	ambient (atmospheric) pressure
p_c	critical pressure for rapid crack propagation
$p_{cFS,S4}$	critical pressure for rapid crack propagation in full scale test, S4 test
p_{res0}	pressure required to reverse residual strain shrinkage
r	radial coordinate from pipe axis
R	variable radius of axisymmetric pipe section
t	time
t^*	normalised time
t_{creep}	time at which creep modulus has been evaluated
u_r, u_θ, u_z	displacements (with dot denoting time derivative)
U_E	external work done per unit pipe length
v	effective opening of crack surfaces, accounting for residual stress closure
V	internal volume of pipe in outflow zone
w	physical opening of crack surfaces
W	pressurised width of model beam
z	coordinate along pipe axis, against direction of crack propagation
α	dimensionless crack velocity
χ_G, χ_L, χ_S	volume proportions of gas, liquid and solid content in pipe
γ	ratio of specific heats for pressurising gas
λ	ratio of outflow length to mean pipe diameter
μ	shear modulus
ϕ	half-angle subtended at pipe axis by crack opening
ϕ_G	half-angle subtended at pipe axis by gaseous proportion of pipe contents
ρ_B	mass density of backfill
ρ_L	mass density of liquid pipe content
θ	circumferential coordinate from plane of crack in pipe
ζ	axial coordinate, normalised against pipe outflow length
d	[as subscript] dynamic value, at time scale of crack driving process
in, out	[as subscripts] at axial positions of upstream and downstream control volume boundary
RCP	rapid crack propagation
S4	small scale steady state (ISO 13477 pipe test method)
FS	full scale (ISO 13478 pipe test method)