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Failure of grey cast iron water pipe due to resonance phenomenon

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ABSTRACT

A condition of resonance in a hydraulic pipe supplied at the upstream end by a reservoir is analysed. The resonance appears in the pipe when the pressure-head at the reservoir vibrates at selected frequencies. The impedance theory is used in the analysis to determine the spectrum of these natural frequencies. For solution, the hydraulic system is programmed on digital computer using the method of characteristics. In these conditions, the pressure-head amplitudes increase gradually and build up to a steady-oscillatory flow. At the downstream dead end of the pipe the pressure can become very large. The effects of energy dissipation resulting from viscous friction are included and show to be of important consequence on the analysed systems. The maximum stresses in the pipes may be calculated via thin-walled hollow cylinder assumptions. In the case were the admissible stress can be reached, this may yield to the failure of the pipe if a corrosion crater exists. To investigate the defect geometry effects, semi-elliptical cracks are deemed to exist up to one-half thickness of the pipe wall. The outcomes have been introduced into the Failure Assessment Diagram (FAD) using the SINTAP code in order to obtain the safety factor value. It has been shown that the value of the safety factor depends on the length of the pipe.

1. Introduction

Most water distribution systems in the world are older than 30 years. The outdatedness of the installations and the poor quality of the pipe materials, which are often corroded or damaged, are responsible for failures. Consequently, a large amount of water is lost by leaks, often more than 30% [1]. Leakage occurs in many components of the distribution system: pipes, service connections, valves or joints. Leaks and failures are a major economic problem. When internal pressure decreases, leaks can also serve as pathways for contamination by harmful organisms from outside the pipes and pathogen intrusions can have health consequences.

Among the most common materials used for water piping – grey cast iron, ductile iron, PVC, cement-based materials and sometimes steel – grey cast iron is an old principal material which has been used for the past 150 years: the majority of distribution piping installed in North America and Western Europe, beginning in the late 1800s up until the late 1960s, was manufactured from this material. Grey cast iron is nowadays always among the most common material used in the water distribution pipes in developed countries. For example, about the half of water distribution networks consists grey cast iron in North America and more than the third in France.

Different types of manufacturing defects that occur in grey cast iron pipes. These defects depend on the manufacturing technique, with pit cast pipes having very different problems from spun cast pipes. Known problems include inclusions, variations in the wall thickness of the pipe along its length, porosity and improper cleaning of the pipe moulds after a pipe has been cast.

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Nomenclature

a	one-half length of elliptical crack
c	crack depth
e	wall thickness
g	acceleration of the gravity
h	oscillatory part of pressure-head
j	linear head loss by unit of length of the pipe
p	pressure
q	oscillatory part of fluid discharge
t	time
x	distance along the pipe
z	elevation
A	cross section area of the pipe
C	pressure wave celerity
C_1, C_2	integration constants
D_e	pipe outside diameter
E	Young modulus of the pipe
F_S	safety factor
H	instantaneous hydraulic pressure-head
$\bar{H}$	average magnitude of pressure-head
K	fluid bulk modulus
K_r	non dimensional stress intensity factor
K_I	applied stress intensity factor
K_{Ic}	fracture toughness of material
K_r^*	ordinate of the assessment point
L_r	non dimensional stress or loading parameter
L_r^*	abscissa of the assessment point
P	internal pressure in the pipe
Q	instantaneous fluid discharge
$\bar{Q}$	average magnitudes of fluid discharge
R	outer radius of pipe
R_c	flow stress
Z	hydraulic impedance
Z_c	characteristic hydraulic impedance
$f(L_r)$	interpolating function
λ	friction factor
v	Poisson's ratio
ρ	is the fluid density
σ_u	ultimate stress
σ_y	yield stress
$\sigma_{\theta\theta}$	hoop stress
ω	angular frequency
ΔH	wave amplitude

Grey cast iron is a material with problems because it is relatively brittle and susceptible to corrode. Due to these defaults and the age of the pipes, grey cast iron is the material that has the highest number of failure per year per kilometre [2].

Programs have been developed to evaluate the degradation state and the risk of failure of pipe systems and to plan their rehabilitation. Preventive and predictive maintenance strategy programs with systems for inspection and control are developed [3–5]. Leakage and cracking of pipes results from the initiation and propagation of defects. Initial defects can be assumed to be corrosion pitting or mechanical damage, e.g., scratches and gouges, occurring during pipeline construction or during in-service maintenance. Variations in internal pressure may be caused by soil-movement induced bending or repeated loading from road traffic. Failure occurs when the defect has reached its critical size, corresponding to service conditions or under unusual conditions, e.g. a water hammer [6,7] or a resonance phenomenon [8].

Periodic oscillations of pressure and discharge in fluid systems have been observed by all of the many investigators in the field of fluid transients. Occasionally the characteristics of a system are such that when a periodic disturbance is introduced to the system, an amplification of the motion occurs resulting in a resonating condition. Numerous descriptions of incidents of resonance in different system types can be found in the literature. Some of them could be explained by various forms of resonance or self-induced oscillations [9,10]. Fig. 1 shows an example of pipeline damaged by the resonance phenomenon.