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Review

Fracture studies of straight pipes subjected to internal pressure and bending moment

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ABSTRACT

Total three straight pipes have been studied which are used in the Primary Heat Transport system of Indian PHWRs (Pressurized Heavy Water Reactor). The pipes have been fabricated with either circumferential throughwall crack or surface crack. Fracture tests have been performed on these pipes subjected to constant internal pressure and monotonically increasing four point bending load. Different experimental and finite element results like load vs. load line displacement, load vs. CMOD (Crack Mouth Opening Displacement), crack initiation loads are compared and found in good agreement. The experimental results have been used for calculation of fracture toughness i.e J-R curves for all three pipes. The differences in these J-R curves have been investigated in the light of prevalent crack tip constraints. Higher J-R curve of surface cracked pipe is attributed to prevalent lower crack tip constraint and vice versa is true for throughwall cracked pipes.

Contents

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Nomenclature

a	initial crack size
A_2	crack tip constraint defining parameter for large strain region
c	half crack length
D_0	outer diameter of pipe
E	Young's modulus
h	triaxiality factor
J	total J-integral (summation of elastic and plastic)
J_e	elastic J-integral
J_i	crack initiation toughness
J_p	plastic J-integral
k	stiffness
K	stress intensity factor
P	total applied load
$P_{0.2}$	experimental crack initiation load corresponding to 0.2 mm crack extension
P_{Ji}	computed crack initiation load corresponding to applied J = crack initiation toughness
p	internal pressure
q	multiaxiality quotient
Q	non dimensional stress triaxiality parameter
R	mean radius
T	transverse stress (valid for elastic field)
T_p	axial force in pipe due to internal pressure
t	thickness
w	width
Δ_{pl}	plastic load line displacement due to crack only
Δa	crack growth
θ	half crack angle in circumferentially cracked pipes
ν	Poisson's ratio
$\sigma_{\theta\theta}$	hoop stress near crack tip
σ_{ys}	yield strength
σ_m	mean (hydrostatic) stress
σ_u	ultimate strength
η_{pl}	a function used to multiply the area under load vs. load line deflection curve to get plastic J-integral
γ	a function used to get plastic J-integral under crack growth situation

Acronyms

ACPD	Alternate Current Potential Difference (instrument for crack growth detection)
BARC	Bhabha Atomic Research Centre
CMOD	Crack Mouth Opening Displacement
CTOD	Crack Tip Opening Displacement
FEA	Finite Element Analysis
FEM	Finite Element Method
IS	Inner Span
LSY	Large Scale Yielding
OS	Outer Span
PHT	Primary Heat Transport
PHWR	Pressurized Heavy Water Reactor
PWR	Pressurized Water Reactor
SERC	Structural Engineering Research Centre
SSY	Small Scale Yielding
SZW	Stretched Zone Width
TPB	Three Point Bending

1. Introduction

In Indian PHWRs, Primary Heat Transport (PHT) piping components contain straight pipes made of carbon steel material SA333Gr6. These pipes are pressurized up to ≈10 MPa under reactor operating condition. These pipes are exposed to different types of operational loadings like thermal stress, internal pressure and self-weight. During accidental condition of earthquake, these pipes are subjected to additional bending moment. Structural integrity assessment of PHT pipes must be done under these postulated accidental conditions for ensuring smooth operation of nuclear reactor. This is especially important when Leak-Before-Break (LBB) concept is applied to design PHT piping of PHWR/PWR. LBB concept is essentially the application of fracture mechanics principles to demonstrate safety of PHT piping components. While applying this concept to Indian PHWRs, several unresolved issues were identified. One of them was the transferability of fracture properties from specimen to components. To address these issues, a comprehensive *Component Integrity Test Program* was initiated by Bhabha Atomic Research Centre (BARC), India in 1998. Under this program, large numbers of straight pipes and elbows were tested in Structure Engineering Research Centre (SERC), CSIR (Council of Scientific and Industrial Research), Chennai [1,2]. In this program, only four point bending moment were applied during test to keep the experiment simpler. However, in actual service condition, the pipes are subjected to combined loading of internal pressure and bending moment. To address this combined effect for better simulation of service condition, another comprehensive test program, *Advanced Component Integrity Test program* was initiated by BARC in 2004. As a part of this test program, three numbers of pressurized pipes were tested under bending moment. Two pipes having nominal diameter of 8-inch sizes with throughwall cracks and one pipe having nominal diameter of 16-inch size with surface crack, have been studied in this paper. These pipes were loaded under constant internal pressure of 10 MPa and subsequently, four point bending moment was monotonically increased during experiments in a quasi-static manner. Different experimental results like total load, load line displacement, CMOD and crack growth were monitored and recorded during fracture tests. Subsequently, three dimensional Finite Element Analyses (FEA) are performed to simulate these tests and different experimental results are compared with FEA predictions.

Using the experimental results of these pipes, the issue of transferability of fracture toughness from specimen to components,