Engineering Fracture Mechanics 162 (2016) 269–289

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

Using unit cell simulations to investigate fracture due to compression–tension loading

Martin Kristoffersen [*], Tore Børvik, Odd Sture Hopperstad

Structural Impact Laboratory (SIMLab), Department of Structural Engineering, Norwegian University of Science and Technology (NTNU), Rich. Birkelands vei 1A, NO-7491 Trondheim, Norway

ARTICLE INFO

Article history:
Received 1 December 2015
Received in revised form 28 April 2016
Accepted 29 April 2016
Available online 14 May 2016

Keywords:
Material tests
Unit cell simulations
Compression–tension load
Ductile fracture
Cleavage fracture

ABSTRACT

Experiments regarding impact against X65 steel pipes show that fracture typically arises in areas subjected to large compressive strains before tension. Fracture surfaces from these areas are brittle in character despite the material exhibiting ductile behaviour elsewhere. Smooth and notched tensile material tests always produced ductile fracture through nucleation, growth and coalescence of voids. The ductile-to-brittle transition seen in the component tests was however recreated in notched axisymmetric material tests, where the specimens were compressed to various levels of plastic strain before being stretched to failure. Increasing compression before tension showed a decrease in strain to fracture as hypothesised, and an increase in the cleavage surface fraction. In an attempt to gain a better understanding of this behaviour, unit cell simulations subjected to tension only and compression–tension loading were carried out. As well as exploring different chosen stress triaxialities, global analyses of the material tests were used to provide an average stress triaxiality for the axisymmetric unit cell simulations. These global simulations were able to represent the material tests with good accuracy. In tension tests where the stress triaxiality was fairly constant (notched tests), the unit cell analyses were able to predict a strain to coalescence within reasonable margin compared with the experimental values. Unit cell simulations including the compressive phase show that the higher the magnitude of the stress triaxiality is during compression, the higher the local stress in the cell, which in turn may trigger cleavage fracture.

1. Introduction

Today and for all foreseeable future, steel pipelines are and will be used extensively for transporting oil and gas. These pipelines are situated in potentially dangerous environments, where impact loads from e.g. anchors or trawl gear pose a particularly hazardous threat [1]. Pipe impact tests have shown that fracture is likely to occur directly underneath the striker during the elastic recovery after maximum displacement [2,3]. In this area of the pipe the material is heavily compressed before the loading is reversed into tension, which can cause a ductile-to-brittle transition [4]. Earlier, Ludley and Drucker [5] made bent-beam tests which emulate the strain history from the pipe (compression followed by tension), and a ductile-to-brittle transition was observed at room temperature for an estimated 60% precompression.

---

[*] Corresponding author.
E-mail address: martin.kristoffersen@ntnu.no (M. Kristoffersen).

http://dx.doi.org/10.1016/j.engfracmech.2016.04.044

Nomenclature

Latin	
a	specimen radius at notch or neck root
A	current cross-sectional area
A_0	initial cross-sectional area
A_r	cross-sectional area at load reversal
b_j	material constants for Voce hardening law
C_i	material constants for kinematic hardening law
D	diameter
D_0	initial diameter
D_r	diameter of specimen in the pipe's radial direction
D_θ	diameter of specimen in the pipe's circumferential direction
E	Young's modulus
E_{11}	mesoscopic strain along radius
E_{22}	mesoscopic strain along circumference
E_{33}	mesoscopic strain along axis of symmetry
E_e	mesoscopic effective strain
E_f	mesoscopic strain to failure
E_r	relative mesoscopic strain to failure
f	yield function
F	force measured by load cell
H	half of height of unit cell
H_0	half of initial height of unit cell
H_c	current half of height of unit cell
H_f	half of height of unit cell at void coalescence
H_r	half of height of unit cell at load reversal
N_V	number of Voce terms in constitutive relation
N_χ	number of backstresses in constitutive relation
Q_j	material constants for Voce hardening law
r	profile radius of neck at the root
R	profile radius of notch at the root
R_0	initial radius of unit cell
R_c	current radius of unit cell
R_H	isotropic hardening variable
R_y	point of re-yielding
U	point of unloading
W_{cr}	plastic "work per volume" to failure by σ_1 when $\sigma_1 > 0$
$\widehat{W}_{\mathrm{cr}}$	plastic work per volume to failure by σ_1
Greek	
γ_i	material constants for kinematic hardening law
ε	strain
$\boldsymbol{\varepsilon}$	strain tensor
ε_{33}	strain along specimen axis
$\varepsilon_{\mathrm{acc}}$	accumulated strain
ε_f	absolute fracture strain
ε_r	relative fracture strain
ε^p	plastic strain
$\boldsymbol{\varepsilon}^p$	plastic strain tensor
$\varepsilon^p_{\mathrm{eq}}$	equivalent plastic strain
ε_U	accumulated plastic strain at onset of necking
$\mathrm{d}\lambda$	plastic parameter
μ	friction coefficient
ν	Poisson ratio
ρ	density
σ	stress
$\boldsymbol{\sigma}$	Cauchy stress tensor
σ^*	stress triaxiality = $\sigma_H/\sigma_{\mathrm{eq}}$
σ_0	yield stress