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Numerical simulation of ductile crack growth in medium wide plate specimens using 3-D computational cells

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A B S T R A C T

This work examines the applicability of a local damage method based on the computational cell methodology, incorporating the Gurson-Tvergaard (GT) yielding model, to predict ductile crack extension of circumferential crack-like defects in Medium Wide Plates (MWP) specimens, extracted from girth welds of pipelines, using standard single edge bend SE(B) specimen and recently standardized clamped single edge tension SE(T) specimens to obtain model parameters. Laboratory testing of SE(B) and SE(T) specimens at room temperature provides necessary and sufficient information to calibrate the parameters of the GT yielding law. After the model parameters have been defined using small specimens, predictions of crack growth behavior can be carried out for other geometries and loading modes. Therefore, parameter transferability between different specimens can be investigated and comparative studies of predicted crack driving forces can be performed. In this study, the simulated tearing resistance curves are compared to experimental data of MWP specimens, where the former is obtained by the cell model calibrated using either SE(T) or SE(B) specimens and the latter is obtained by large-scale experiments. Overall, a good agreement between numerical and experimental $\delta - \Delta a$ curves was observed demonstrating that the cell methodology can be considered as a valid engineering tool for studying the integrity of structural components.

1. Introduction

The efficient and safe use of the fracture mechanics approach to the design of new structural components and repair decisions of typical in-service flaws assumes that fracture toughness values measured from testing standard specimens are a material property. Within this methodology, experimentally measured fracture toughness values can be *transferred* in a rather straightforward manner to structural applications provided the crack-tip conditions between the laboratory specimen and the structure are presumably similar (see, *e.g.* - Hutchinson [1] and Anderson [2]). However, while single-parameter fracture mechanics approaches provide a generally conservative acceptance criterion for cracked structural components by relating the operating conditions to a critical applied load or critical crack size, these approaches are not appropriated to describe adequately the crack-tip stresses and strains which drive the fracture process when large-scale plasticity develops in the specimen or structure. A particular case of considerable interest lies in direct application of crack growth resistance ($J - \Delta a$ or $\delta - \Delta a$) curves (also often termed *R*-curves) measured using small laboratory specimens to surface defects in larger

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Nomenclature

σ_e	effective von Mises stress
σ_m	mean hydrostatic stress
$\bar{\sigma}$	current flow stress of the cell matrix material
f	initial void volume divided by cell volume
q_i $(i = 1, 2, 3)$	dimensionless factors to improve cell response
f_E	critical void value
D	cell size
a	crack depth
c	crack length
n	strain hardening exponent
K	strength coefficient
Δa	amount of stable crack growth
H	length of SE(T) specimen
S	unsupported span of the SE(B) specimen
D'	external pipe diameter
t	pipe wall thickness
W'	width of the Medium Wide Plate specimen
L	length of the prismatic section of Medium Wide Plate specimen
$2h$	weld groove width
B	specimen thickness
B_N	net specimen thickness
δ	crack tip opening displacement (CTOD)
J	J-integral
a/W	crack size ratio
σ_{ys}	tensile yield strength
σ_{uts}	ultimate tensile strength

structural components. However, laboratory testing of fracture specimens to measure resistance curves consistently reveals a marked effect of absolute specimen size, geometry, relative crack size (a/W) and loading mode (tension vs. bending) on *R*-curves. These effects arise from the strong interaction between micro-structural features of the material, which govern the actual separation process, and the loss of stress triaxiality in the crack front region due to large-scale yielding.

The latter is often referred to as crack-tip constraint. This constraint, for either a structural component or a test specimen, can be interpreted as the ability to deform plastically under increasing levels of remote applied load. Current engineering approaches for defect assessments make extensive use of fracture toughness values measured from testing high constraint fracture specimens, such as deeply-cracked C(T) or SE(B) geometries, to characterize the material fracture behavior at a specific temperature. However, structural components, that have been just manufactured or have been operating under normal conditions, usually contain shallow cracks which are associated with low levels of constraint. Thus, direct application of fracture toughness data from high constraint specimens to low constraint structures often introduces high levels of conservatism during the engineering analysis which are associated with unknown levels of safety. Consequently, advanced methodologies for structural integrity assessments endeavor to utilize fracture toughness data obtained from low constraint fracture specimens to provide more adequate safety levels in design and in-service operation producing less conservative, but yet reliable, engineering structures.

Within this context, recent fracture assessment guidelines recommended by Det Norske Veritas [3] and British Standard [4] advocate the use of single edge notch tension (SE(T)) specimen under clamped conditions to characterize the fracture properties of high pressure piping systems. The primary advantage to use SE(T) specimen to describe the fracture toughness curve is the similarity in the crack tip fields (stresses and strains) between the SE(T) geometry and pipeline girth welds under global bending. Another advantage of this specimen is that the actual crack depth in the SE(T) specimen is not essential for obtaining a representative $\delta(J) - \Delta a$ curve, as long as it is between $0.3 \leqslant a/W \leqslant 0.5$ [5]. This feature has also been observed by previous numerical simulations [6]. Recent applications of SE(T) specimens to characterize crack growth resistance properties in a high strength API 5L X100 steel [7] have been effective in providing large flaw tolerances and reducing the excessive conservatism obtained with testing of high constraint specimens.

Another geometry that deserves attention is the Curved Wide Plate (CWP) specimen. The CWP was introduced by researchers of University of Ghent in Belgium in the 1970s [8]. The CWP specimen takes into account different factors such as crack-tip constraint, component scale volume sampling, and heterogeneous mechanical properties in welded joints affecting the response of real welded structures - including - pipelines, pressure vessels, and naval applications. These structures are typically subjected to membrane tension loads, that is, small stress variation through the thickness direction. In the case of pipelines, a curved wide plate (CWP) is extracted from the girth welds and has the advantage of behaving (in mechanical