Engineering Fracture Mechanics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

Simulations of the large-scale four point bending test using Rousselier model

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ARTICLE INFO

Article history:
Received 3 August 2016
Received in revised form 15 February 2017
Accepted 17 February 2017
Available online xxxx

Keywords:
Large-scale four point bending test
Finite element analysis
Circumferential through-thickness crack
Welded Residual stress
Rousselier damage model

ABSTRACT

STYLE or "Structural integrity for lifetime management-non-RPV component" was a EURATOM Framework 7 project which try to develop a new understanding of the combined influence of mechanical loading and residual stresses on the ductile fracture behaviour. The project was divided into two main parts, i.e. experimental part and the simulation part. The work presented in this paper relates to the simulation part of the STYLE project. The paper presents the results of a ductile damage mechanics procedure that was developed to predict ductile crack extension under a combination of primary and weld residual stress in a large-scale four-point bending test performed on a repair welded Esshete 1250 pipe containing a circumferential through-thickness crack. In this work, a finite element model of the test was created in ABAQUS, and the weld residual stress was introduced to the model by an iterative technique. The Rousselier model was calibrated against the ductile fracture behaviour of a test specimen including crack initiation and growth. The prediction of final crack growth in the large-scale test obtained from this analysis is compared with the results obtained from a fracture mechanics analysis based on the *J*-integral and the large-scale test outcome. The Rousselier model and the fracture mechanics approach predicted a similar amount of ductile tearing to the average amount of crack extension observed in the large-scale test, with any slight differences likely to be an artefact of either non-symmetric loading in the test, or differences between test weld residual stresses or material properties compared with those measured on "sister" specimens. The shape of the crack growth was well predicted by both approaches.

1. Introduction

It is well known that the residual stresses, which arise in welded joints due to strains caused by solidification, phase change and contraction during welding, have a significant influence on failure behaviour of engineering structures. Residual stresses can combine with service stresses to increases the potential for crack initiation and lead to higher rates of growth of defects, or even initiate cracking before a component is subjected to service loads [1–3]. The study carried out by Ren et al.

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http://dx.doi.org/10.1016/j.engfracmech.2017.02.015
0013-7944/

Please cite this article in press as: Arun S et al. Simulations of the large-scale four point bending test using Rousselier model. Engng Fract Mech (2017), http://dx.doi.org/10.1016/j.engfracmech.2017.02.015

Nomenclature

D	Rousselier model's parameter
f	void volume fraction, the volume fraction of cavities
f_0	initial void volume fraction
J	J-integral
K_I	mode I stress intensity factor
L_c	the characteristic length or the mesh size
p	pressure
q	von Mises equivalent stress.
ϵ_{eq}	equivalent plastic strain
ρ	mass density, relative density
σ_1	Rousselier model's parameter
ϕ	yield function or plastic potential

[4] confirms that the residual stress can significantly elevate the crack-tip constraint which results in an increase of the probability of cleavage fracture in ferritic steels. In addition, a tensile residual stress can significantly reduce the apparent ductile crack growth resistance when the crack growth is small [5]. It is, therefore, necessary to study the effect of residual stress on various aspects of failure in order to perform accurate and reliable structural integrity assessments.

As the residual stress fields containing in welded components are always complex in form, validated methods for predicting the failure behaviour of welded structures, particularly if non-stress relieved, are desirable. At present, finite element (FE) analysis is widely accepted as a popular tool for the prediction of defect behaviour in engineering component. Accordingly, residual stresses can be introduced into the analysis via two main methods. The first method is to introduce the residual stress via plastic deformation which requires a knowledge of the history of the prior deformation in the structure. A second method is to specify the residual stress directly at the integration points of the model as an initial stress. This method requires a definition of the stress field in the initial condition of the structure.

The prediction of failure in large-scale structures is required by a number of industries including the oil and gas, nuclear and aerospace, and a number of fracture mechanics approaches have been developed to do so, including API 579-1/ASME FFS-1 which sets out a number of fitness for service procedures used in the oil and gas, petrochemical and chemical industries [6], and BS7910 [7]. In the nuclear sector, the R6 defect assessment procedure is widely used [8].

These approaches tend to use the principles of fracture mechanics which provide a conservative approach to the prediction of failure, particularly where defect loading includes a component of residual stress, e.g. due to welding. For example, Lei et al. [9] demonstrated the conservatism of BS7910 for assessing several types of defect in girth welds. Similarly, Swankie et al. [10].

The conservatism in fracture mechanics-based assessments of pipes containing defects has led to the assessment of damage mechanics approaches for the prediction of ductile failure in pipes [11], applied the Gurson-Tvergaard-Needleman (GTN) model [12,13] to predict the behaviour of a number of external circumferential pipe defects loaded by a combination of internal pressure and remote bending. The results demonstrated that the GTN damage mechanics model, calibrated against single edge cracked tension (SENT) fracture toughness results, was able to predict crack initiation and growth in the tests. This work has been extended to assess the influence of weld residual stresses on ductile fracture in SENT specimens [14]. For this geometry, residual stresses were found to have little influence on fracture strength.

The work presented in this paper builds on these studies to assess the ability of a ductile damage mechanics approach to predict crack growth in a pipe weld containing a non-stress relieved weld repair. This extends these previous studies to incorporate not only primary loading, but also high and non-uniform weld residual stresses in a structural pipe geometry. The resulting simulation was part of the STYLE project [15]. It aims to present a finite element and damage mechanics approach which can used to assess failure in welded components. The central focus of this paper is to describe the ductile fracture behaviour of a large scale bending test conducted at CEA as part of EU-STYLE [16]. The test was carried on a repair-welded pipe that contained a circumferential through-thickness crack. The test specimen, called Mock-Up 2 (MU2), was manufactured from two Esshete 1250 stainless steel pips joined by a girth weld. The weld contained a short, deep weld repair and a through thickness pre-crack that was inserted at the centre of the repair. Before testing, both ends of the MU2 test piece were welded to extension arms created from 304L stainless steel to provide bending span. The main section of MU2 and the pre-crack position are shown schematically in Figs. 1 and 2. More details of this experiment had been already explained in Section 2.

In this work, the FE model of the MU2-test was created in ABAQUS, and the weld residual stress fields were introduced into the welding section of the model as initial stress by using iterative technique [17]. The Rousselier model was employed to predict the failure behaviour, such as crack initiation position and load, crack propagation profiles and final crack growth,

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