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Measurement and modelling of *R*-curves for low-constraint specimens

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ABSTRACT

R-curve testings of Grade X65 pipeline steel girth weld for low-constraint specimens were investigated experimentally. Single-edge-notched bending (SENB), single-edge-notched tension (SENT) and central-cracked tension (CCT) specimens were used to measure *R*-curves using the unloading compliance method. The recently developed single specimen unloading compliance for SENT specimens was validated using the multiple specimen method. Based on the test results, three constraint parameters (*T*-stress, *Q*-stress and A_2) were used to derive constraint-dependent *R*-curves. A comparison of the predicted constraint-based *R*-curves against the test result was given. It is shown that all three constraint parameters can be effectively used for obtaining *R*-curves under low-constraint levels. The modelling method can potentially be used for engineering critical assessment (ECA) in various industry sectors.

1. Introduction

A tearing resistance curve, or *R*-curve, represents a material's resistance to progressive crack extension (this implies that a material's fracture toughness can change with crack extension). Hence, a tearing resistance curve is a plot of fracture toughness against crack extension (e.g. J vs. a or CTOD vs. a, where a is crack extension). The *R*-curve represents a material property in terms of its fracture behaviour and is usually required for engineering critical assessment (ECA) of ductile materials.

R-curve testing procedures for high-constraint specimens, such as deeply notched SENB (single-edge-notched bending) and CT (compact tension) specimens, have been well-established in many standard codes such as BS 7448 [1] and ASTM E1820 [2]. These standards allow the choice of multiple or single-specimen techniques to determine an *R*-curve. The multiple specimen technique requires testing several specimens to determine a single *R*-curve for a specific material, which results in a high material and labour cost. In contrast, the single-specimen method requires in principle only one specimen to determine a full *R*-curve for a given material. The single-specimen technique relies on indirect methods for measuring the crack extension. The most common approach to determine the crack extension during the test is through either the unloading compliance or the electric potential drop method.

It is known that *R*-curves depend significantly on constraint levels at the crack tip, which vary according to specimen type, size and loading types (Fig. 1) [3]. This is the so-called transferability problem. It has been suggested that use of low-constraint specimens such as SENT (single-edge-notched tension) and shallow-notched SENB specimens will allow improved estimates of fracture toughness to be obtained that are appropriate for the assessment of circumferential flaws in pipe girth welds [4]. As a result, it is becoming the industry norm in offshore industry to use SENT specimens to determine the *R*-curve of pipeline girth welds under high strain [5,6].

Although methods for *R*-curve testing of low-constraint specimens have been under development for some time in a number of research centres around the world, the standardisation of those methods is limited. Generally, there is insufficient

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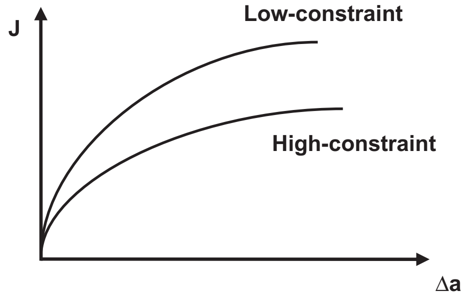

Fig. 1. Constraint effect on *J–R* curves.

clear guidance in national and international test standards on the testing of low-constraint specimens and the interpretation of test results. Use of the single-specimen technique for generating the *R*-curve using low-constraint specimens is rather limited.

An alternative solution for transferability problems in fracture toughness is to predict the *R*-curve mathematically rather than experimentally measure the *R*-curves using low-constraint specimens. In this case, two-parameter fracture mechanics theory should be used for describing the stress, strain or displacement field at a crack tip for different degrees of constraint. Constraint-based approaches for determining the material fracture initiation toughness J_{1c} are described in industry codes such as R6 [7] where empirical formulas to calculate the *T*-stress and *Q*-stress have been given. However, these codes tend not to give a quantitative description of the effect of constraint on the *R*-curve.

The present paper investigated the experimental procedures in measuring the *R*-curve for low-constraint specimens including SENB, SENT and CCT (central-crack in tension) specimens. The particular focus is on the validation of the unloading compliance method for SENT specimens. This is because the unloading compliance method for testing SENT specimens was developed recently [8] and there is a lack of comparison of the result between using the multiple specimen method and the single specimen unloading compliance method. The *R*-curve modelling will use three different constraint parameters (*T*-stress, *Q*-stress and A_2) to derive a generalised *R*-curve which is a function of constraint levels.

2. *R*-curve testing

2.1. Material

The pipeline girth weld joint with nine passes in Grade X65 pipeline steel was used for the fracture testing. The pipe has an outer diameter of 970.2 mm with a wall thickness of 27.8 mm. The choice of this particular material is mainly because the welded joint was already available at TWI and had already been characterised in terms of *R*-curves. This material is widely used in the pipeline industry and it is considered that this material choice will have insignificant effects on the generality of the methodologies to be investigated.

Uni-axial tensile tests were carried out in accordance with BS EN 10,002:2001 [9]. Cylindrical tensile specimens were machined and tested. Two specimens were machined from a section of parent material and the specimens were taken longitudinally and tested at ambient temperature. For the weld, two specimens were machined from the girth weld for the all-weld metal test.

Tensile property data from the experimental tests are summarised in Table 1 for both parent and weld material. Fig. 2 gives a comparison of the stress–strain curve between parent and weld material. It can be seen that the mis-match between parent material and weld is approximately 20%. Although the weld metal shows discontinuous yielding, the two curves approach each other at a strain of 2%.

The mis-match (heterogeneity in deformation properties) may have substantial effects on the crack driving force. The effect of mis-match on crack driving force has been investigated by many research laboratories. Schwalbe et al. specified windows within which test methods developed for homogeneous materials can be used [10]. It was recommended that when the mis-match level $0.5 \leqslant M \leqslant 1.3$ (M = weld metal yield strength/parent yield strength) and $0.1 \leqslant a/W \leqslant 0.7$ (a/W = the crack length/specimen width), the equations to calculate crack driving force for homogeneous materials are also applicable

Table 1
Tensile properties of parent and weld material (*P* – parent material, *W* – weld material).[a]

Specimen ID	0.2% proof strength (MPa)	Stress at 0.5% strain (MPa)	Tensile strength (MPa)	EI (%)
P01–01	479	486	568	**25**
P01–02	477	483	563	**25**
W01–09	576	576	650	**25**
W01–10	573	575	647	**24**

[a] The material properties are expressed in engineering stresses.