DUCTILE FAILURE OF HIGH TOUGHNESS LINE PIPE CONTAINING CIRCUMFERENTIAL DEFECTS

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1. INTRODUCTION

The acceptability of imperfections detected in pipeline girth welds is generally determined with respect to maximum allowed sizes based on workmanship standards for particular types of imperfections in pipeline standards such as CSA Z184, API 1104 and B.S. 4515.

In some cases, however, the acceptability may be determined on the basis of an Engineering Critical Assessment (ECA) using a fracture mechanics analysis. A series of full scale fracture tests in girth welds containing defects was designed and conducted in a joint program at the University of Waterloo and the Welding Institute of Canada under the sponsorship of NOVA, An Alberta Corporation, and subsequently by the American Gas Association. The majority of the tests were performed on 914 mm and 1067 mm diameter spiral welded pipe using a distributed bending load and have been reported in previous publications [1,2].

Previous analysis of these tests [2] showed that the methodology of British Standard PD 6493 was conservative by at least a factor of 2 on the strain at failure or defect depth, except for tests of longer defects in which ductile failure occurred by stable tearing through the remaining ligament.

Calculations have shown that in a number of these tests failure occurred near the maximum bending moment for an ultimate ductile failure of the pipe. To investigate this further, calculations have been made to relate failure to the reaching of the flow stress in part or all of the pipe. Calculations were also made for flat plate tensile tests undertaken by the authors, pipe and plate tests undertaken by Erdogan et al [3] and pipe tests undertaken by Wilkowski and Kanninen [4] and Wilkowski and Eiber [5].
2. NET SECTION FLOW

Net section flow can be defined as occurring when the average stress in the material at the plane of the defect reaches the flow stress. The flow load is then dependent on the definition of the flow stress and the dimensions of the specimen and defect. For materials such as line pipe steels with little strain hardening the flow stress can be reasonably assumed to be the average of the yield and ultimate stresses. For materials with more significant strain hardening this definition of flow stress is undoubtedly more approximate in representing the average stress across the section.

In the following sections data from various sources is studied to indicate if failure of flat plates in tension and pipes in bending can be predicted from net section flow or similar behaviour.

3. FLAT PLATE TESTS

To examine the fracture behaviour of high toughness line pipe material (CSA Z245.1 Grade 483), a number of tensile and bend specimens were loaded at room temperature under displacement control until a maximum load was exceeded. The results indicate that the maximum load, \( P_L \), corresponded to a condition of flow stress on the net section at the plane of the crack. These limit loads were calculated using the following relations for surface defects in tension:

(i) Elliptical crack, \( P_L = \sigma_f (Wt - \frac{ac}{2}) \),

(ii) Edge crack, \( P_L = \sigma_f W(t-a) \),

(iii) Centre crack, \( P_L = \sigma_f t(W-2c) \).

For surface defects in bending the relationship was:

(iv) \( P_L = \sigma_f \gamma W(t-a)^2/4S \),

where \( P_L \) = limit load; \( \sigma_f \) = flow stress; \( W \) = total width; \( t \) = thickness; \( a \) = crack depth; \( 2c \) = crack length; \( S \) = span; \( \gamma = 1.543 \) (for sharp crack), or \( 1.261 \) (for blunt notch).

The results of the tests and analyses for flat plates are given in Figure 1. All of the results are either conservative or are within one percent of the predicted limit load. Further confirmation of this analysis is found by considering data recently published by Erdogan [3] for