Flaw Tolerance of Pipelines Containing Circumferential Flaws Subjected to Axial Straining and Internal Pressure—Tests and Analyses

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A number of codified assessment procedures can be applied to assess the significance of circumferential flaws in pipes, but these are generally stress-based. Efforts have been made to extend these so that they are applicable when the pipe is subject to axial plastic straining with and without internal pressure. In this paper, the results are presented for two full-scale tests that were axially loaded beyond yield. The tests were conducted on the parent pipe to API 5L PSL 2 Grade X65, 273.3 mm OD × 18.4 mm WT, which contained circumferential surface notches. In the first test, the pipe was axially strained until failure, and in the second test, the pipe was first internally pressurised and then axially strained until a failure condition was reached. In both tests, failure was ductile. The full-scale tests were accompanied by small-scale tests, which included SENT tests to derive fracture toughness resistance curves. For the materials investigated, the SENT specimens with EDM notches produced resistance curves almost identical to those with fatigue precracks. The behaviour of the pipes in terms of CTOD versus applied strain was compared with finite element analyses and failure analysis diagram (FAD) methods described in BS 7910. It is shown that a modification of the material-specific FAD enables it to be extended up to 3% strain.

INTRODUCTION

There are several recently developed methods for assessing the strain capacity of pipelines containing circumferential surface flaws, although these are not yet codified (Ostby and Hellesvik, 2007; Fairchild et al., 2011; Wang et al., 2012). They have been developed through a combination of numerical analysis and full-scale testing. FAD-based methods have received less attention, but general approaches have been suggested (Budden and Smith, 2009; Smith, 2012). This paper describes some initial results from a project whose primary objective is to develop a strain-based flaw assessment procedure, which quantifies the most important variables that influence flaw tolerance of pipeline girth welds subjected to axial plastic straining with and without internal pressure. If it can be shown to be possible, the intention is to extend FAD methods, described in BS 7910, beyond yield into the plastic straining regime. This objective is being achieved through a series of numerical analyses of pipes containing circumferential flaws, material characterisation, especially fracture toughness, full-scale pipe testing, and analytical work. This paper describes the results and analyses of the first two full-scale pipe tests. The tests were conducted on the seamless pipe to API 5L PSL 2 Grade X65 with an average outside diameter of 273.3 mm and a wall thickness of 18.4 mm. Four notches were introduced by electro-discharge machining (EDM) into the pipe outside diameter in the circumferential direction, with notches at 12, 3, 6, and 9 o’clock. The first pipe was plastically loaded in tension until failure. The second pipe was first internally pressurised to 620 barg with water to produce a hoop stress of approximately 87% of the parent pipe yield strength. Subsequently, the pipe was axially loaded in tension until through pipe wall tearing (and a leak) occurred from one of the notches. Each pipe was instrumented to record the pressure, applied force, local strain, overall strain, and crack mouth opening of each of the notches. The results were analysed to provide the relation between stress and strain, local strain and remote strain, and CTOD and strain. In addition, the CTOD values predicted from finite element analyses with and without correction for ductile crack extension were compared with the experimental data. Finally, a comparison was made between CTOD obtained from the pipe and CTOD derived from J-integral using a conventional (BS 7910 Level 2b) stress-based and a new strain-based FAD.

EXPERIMENTAL DETAILS

Pipe Material and Properties

The project used the seamless pipe to API 5L PSL 2 Grade X65 with an outside diameter of 273.3 mm and a wall thickness of 18.4 mm. Testing showed that the average yield strength $(R_{0.2})$ was 512 MPa and the tensile strength $(R_m)$ was 597 MPa in the longitudinal direction. The highest, lowest, and mean engineering stress-strain curves obtained from a series of eight specimens taken from around the circumference of the pipe are shown in Fig. 1. In the circumferential direction, tensile properties were determined by using 8-mm round bar specimens, which resulted in yield and tensile strengths of 522 and 608 MPa, respectively; these differ by less than 2% of the longitudinal values. The parent pipe specimens exhibited an upper yield and a Lüders plateau extending for about 1.9% strain before work hardening started at a strain of 2.3%. The strain at the tensile strength was approximately 11%. In subsequent analyses, the upper yield was ignored, and the mean stress-strain curve shown in Fig. 1 was used.

Fracture toughness was determined by using single edge notch tension (SENT) specimens based on the design and testing method described in DNV-RP-F108 (2006). The specimen had an over-square cross-section $(2B \times B$, where $B$ is 16 mm; this corresponds to the pipe wall thickness after machining to remove curvature), with crack depth to width ratio $(a/W)$ of approximately 0.3. The specimens were notched from the pipe OD by EDM, then fatigue precracked to achieve the final crack depth. In addition, a set of tests was conducted using EDM notches located in the weld metal of a girth weld, which was tested for a subsequent phase of the