Full Scale Testing of Large Diameter Pipelines

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ABSTRACT

Current interest in fitness for purpose evaluations of defects in pipeline girth welds indicate the necessity of studying the various proposed fracture mechanics approaches on full size pipe. This paper describes a program to construct a large pipe test facility for full scale fracture tests of pipeline girth welds containing fatigue sharpened defects.

KEYWORDS

Pipelines, girth welds, fracture mechanics, fitness for purpose, full scale pipe fracture tests.

1.0 INTRODUCTION

The significance of defects in pipeline girth welds has been a subject of considerable interest in recent years. The recent investigation of weld defects in the Alyeska Pipeline [1] is a well known example of fracture mechanics principles being applied in a "fitness for purpose" approach. A number of studies [2] have indicated a lack of data on the behaviour of defects in full scale girth welds which could be used to provide confidence in fracture mechanics analyses based on the results of small scale tests. Three full scale tests on girth welds done for the American Gas Association (A.G.A.)[3] and a few tests done by private organizations are the only sources of data.

The Alberta Gas Trunk Line Co. Ltd. and its subsidiary Foothills Pipe Lines (Yukon) Ltd. are sponsoring the Welding Institute of Canada and the University of Waterloo to construct a facility for the full scale testing of girth welds and a series of bending tests on 914 mm diameter, 11.4 mm thick, pipe. The experimental results from the program will be used to evaluate the accuracy of fracture mechanics predictions of the behaviour of weld defects in full scale girth welds.

This paper discusses the construction and commissioning of the facility, the technique for producing fatique sharpened defects in the girth welds and the test program.

2.0 FAILURE MODES

Failure of the test pipe with an internal surface defect in the girth weld at the point of maximum tensile bending stresses is expected to occur by either fracture or by plastic collapse of the ligament over the defect.

2.1 FRACTURE

UNIAXIAL LOAD

Since fracture initiation in pipeline girth welds is likely to take place by an elastic-plastic failure mode, the fracture mechanics analysis procedure outlined in the draft British Standard [4], has been used for the calculation of the tolerable defect size. The relationship between crack opening displacement (COD), δc, the total strain, ε, the yield strain εy and the tolerable flaw parameter $\bar{a}_{max}$ is given as

$$\bar{a}_{max} = \frac{\delta c}{2\pi \ (\varepsilon - .25\ \varepsilon y)} \quad \text{for} \quad \varepsilon > 0.5\ \varepsilon y$$

BIAXIAL LOAD

Most of the analyses referenced above have assumed that the longitudinal stress alone (including residual stress) has the major influence on circumferencial fracture [2]. However the effect of a biaxial stress state on elastic-plastic fracture parameters has been studied by Miller and Kfouri [5,6]. They analyze their results in terms of λ, a biaxiality parameter and the plastic zone size. The three areas studied were $\lambda = 0$ (uniaxial tension), $\lambda = +1$ (equibiaxial load) and $\lambda = -1$ (shear loading). Using $\lambda = 0$ as the reference point, in the case of $\lambda = +1$ the plastic zone size is slightly reduced and when $\lambda = -1$ the plastic zone size is markedly increased. Therefore, in the case of $\lambda = +1$ the fracture toughness would be reduced and when $\lambda = -1$ the toughness should be marginally increased. That is the effect of internal pressure on pipe failure should be to reduce the plastic zone size and decrease the toughness slightly.

2.2 PLASTIC COLLAPSE

Work by Wilkowski and Eiber [7] shows that failure by plastic collapse of the remaining ligament occurring in pipes with surface grooves can be related to the flow stress and the groove geometry. For the typical defects being tested plastic collapse will lead to slow tearing through the wall to give a through wall defect followed by unstable fracture if the applied stress is greater than 95% of the flow stress.

3.0 FULL SCALE TEST FACILITY

The pipe test facility shown in Fig. 1 was designed and constructed by the Department of Mechanical Engineering of the University of Waterloo. Capable of full scale bend testing of pipes up to 1422 mm in diameter and 19.0 mm wall thickness the facility consists of:

(1) the reaction beam and tie rods
(2) the hydraulic loading system and saddles
(3) the support frame

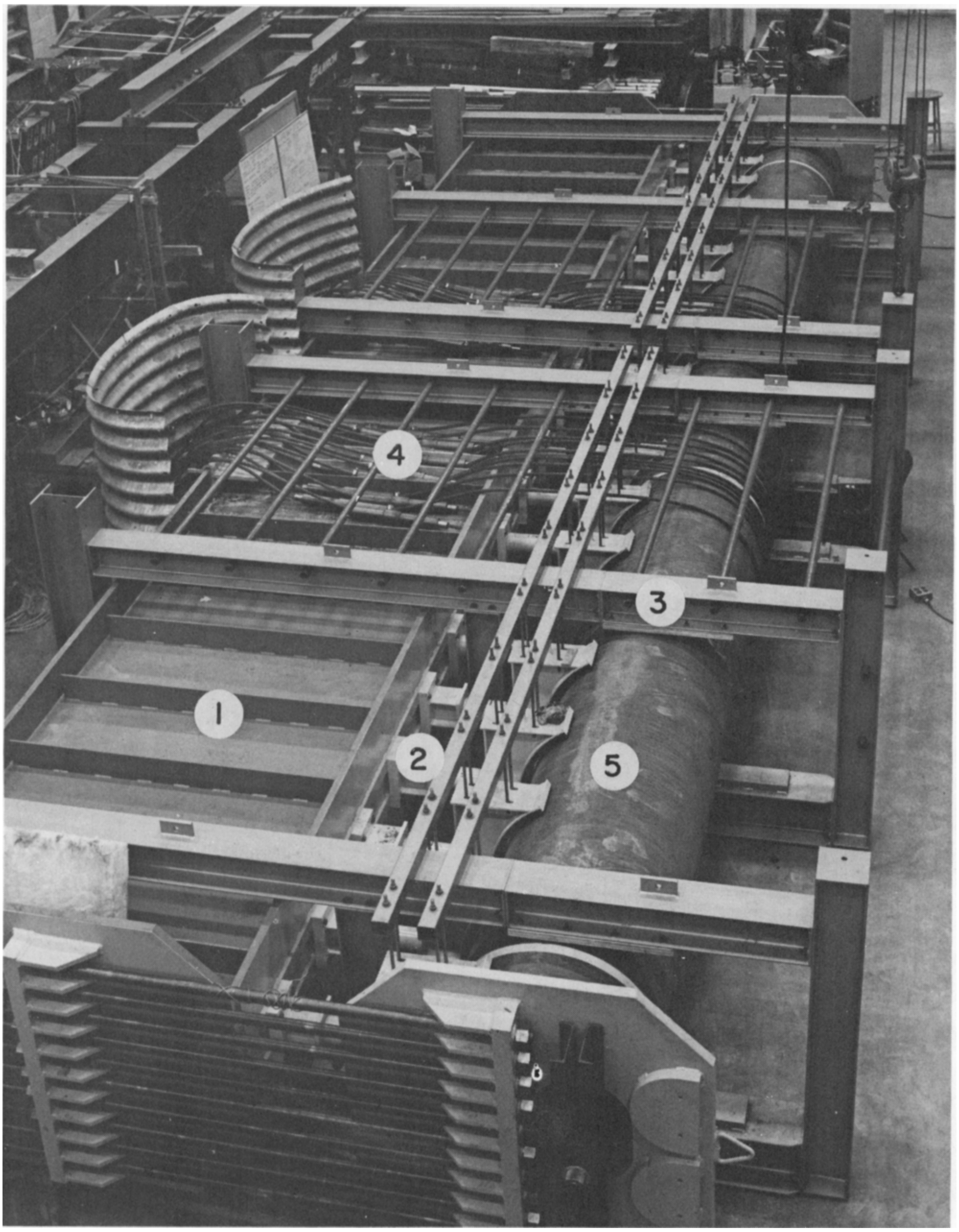

Fig. 1. Full scale pipe bend test facility.

(4) the safety restraint system
(5) the test pipe
(6) the local cooling jacket (not shown)
(7) the internal pressure system (cannot be seen)

In the configuration shown, a pipe specimen 12.2 metres long is attached to the reaction beam by tie rods. A series of twenty 50 ton hydraulic jacks positioned between the reaction beam and the pipe apply a distributed load through a series of saddles. The spacing and size of the saddles were designed to prevent local buckling and remove the necessity for internal pipe reinforcement. The bending moment occurring at the centre of the pipe is approximately constant over the length of the test section which usually contains the girth weld being tested. The restraint system has been designed to retain a 1422 mm diameter pipe during a rapid failure of the central girth weld. The system consists of one 22 mm diameter wire rope running through the centre of the pipe to prevent longitudinal separation of the pipe and twenty 22 mm diameter wire ropes surrounding the pipe and reaction beam (Fig. 1). To prevent shock loading and dissipate energy, a shock absorbing system based on the crushing of a mixture of lead and polyethylene pellets has been built into each wire rope. Jack pressure is supplied by an electrically driven hydraulic pump and is controlled accurately by a servo valve and servo controller. Pressure is indicated by a strain gauge pressure transducer.

The test program makes use of the 12.2 metre length of pipe (Fig. 1) used for commissioning with pup sections containing the girth weld and/or defect being welded into the central portion of the pipe. Each test section is longer than the previous section to avoid rewelding in the same position on the original commissioning test pipe. Test sections containing girth welds have been produced using field welding procedures by the sponsor. The pipe has a yield stress of 521 MPa and an ultimate tensile strength of 653 MPa.

3.1 INTERNAL PRESSURE DEVICE

To study the effect of internal pressure a special device was constructed which allowed the application of internal pressure at the same time as longitudinal bending stress. The use of hydraulic or gas pressure was not practical as the ovalling of the pipe during the bend test was substantial and would make sealing difficult. Although this may be overcome by correct seal design, failure of the pipe would undoubtedly destroy the accurate tolerances required in such a seal. Therefore the internal pressure device shown in Fig. 2 was developed [8].

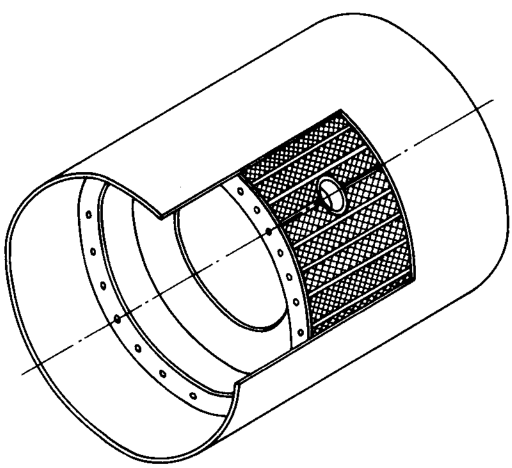

Fig. 2. Internal Pressure Device

The device consists of an internal cylinder (76 cm diameter) supported against buckling by two diaphragms. During assembly the annulus between the internal pipe and the test pipe is filled with strips of neoprene. Twenty four 19 mm tie rods run longitudinally in the annulus passing through thick quadrant rings at the ends. Tightening of nuts on the tie rods compresses the rubber longitudinally. For high compressions the neoprene reacts as a fluid exerting pressure in all directions, simulating an internal pressure on the pipe. Sheet metal shims are used in various locations to prevent extrusion of the neoprene.

To allow instrumentation of the defect on the inside of the pipe a thick walled cylinder passes through the internal pipe and rubber, butting up against the internal surface of the test pipe. To prevent local bending from occurring this thick cylinder is sealed and pressurized with nitrogen gas. If the pressure of nitrogen gas exceeds that in the rubber the gas leaks away. This has proven to be an excellent way of measuring the pressure generated in the rubber. The pressurized thick cylinder also has sealed electrical connections passing through the end closure.

Commissioning of the internal pressure device has shown it to be rugged and function well up to pressures of 9.65 MPa. Unfortunately there is some pressure variation that occurs when the pipe ovals during the bending test.

3.2 LOW TEMPERATURE APPARATUS

To cool the girth weld and/or defect during test a cooling device has been constructed. Consisting of a cold box and a cool down ring it is used to circulate cold nitrogen gas around the pipe. Liquid nitrogen is evaporated in the cold box and forced by a fan to circulate around the pipe in two passages of the cool down ring. The full circumference of the pipe is cooled evenly over a length of 30 cm. As the temperature gradient produced is axisymetric and away from the weld/defect no thermal stresses are created.

Commissioning tests have shown that temperatures between -25°C and -90°C can be obtained to ± 2°C and held constant by controlling the liquid nitrogen supply.

3.3 COMMISSIONING TEST

To commission the loading frame and demonstrate its function a 12.2 metre length of 914 mm diameter, Grade 483 MPa, 11.4 mm wall thickness, spiral-welded pipe was loaded to 90% of its yield strain. The pipe and test facility were extensively strain gauged with 29 strain gauges concentrated in the central region to determine strain levels and pipe behaviour. Measurements of pipe ovality were also made.

For the commissioning test the jack pressure was determined from two Bourdon tube pressure gauges. It was determined that the accuracy of these gauges was ± 3% and therefore for subsequent tests the more accurate servo controlled system described previously was used. Pressure was applied to the jacks in increments of .35 MPa up to 13.8 MPa with strain gauge readings being taken at each increment.

The results from the strain gauges at the pipe centreline on the inside and outside respectively are given in Fig. 3 and compared with the theoretically calculated strains. It can be seen that the strains are behaving linearly, however are approximately 5% less than the theoretically predicted values. This error is considered to be partially due to the lack of accuracy in the pressure measurement (3%) and friction in the loading system and ovalling of the pipe (2%).

To aid in the design of an internal pressure device and to further explain the

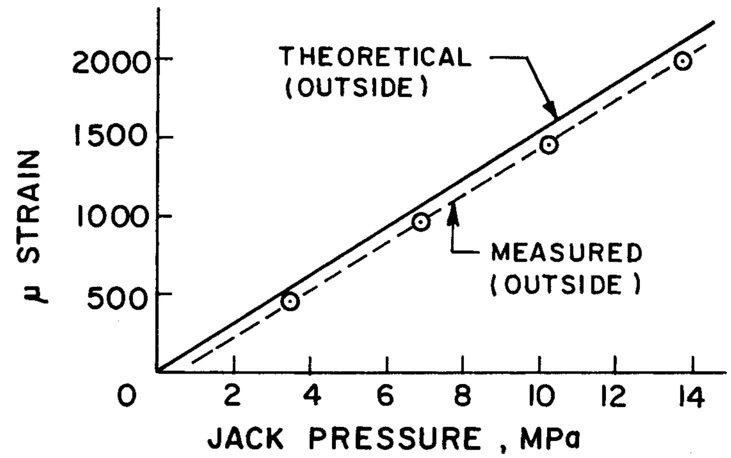

Fig. 3. Comparison of measured and theoretical strains during commissioning test (centre strain gauge)

discrepancy in measured strains, a study was made of the ovality developed in the pipe during loading. Fig. 4 has been prepared from the results. It should be noted that although the ovality is small it will have an effect on strain levels in the pipe. The effect is complex as ovalling will reduce the moment of inertia of the pipe, increasing the strain levels at a given pressure and will also reduce the distance from the neutral axis to the outer fibre reducing the strain levels.

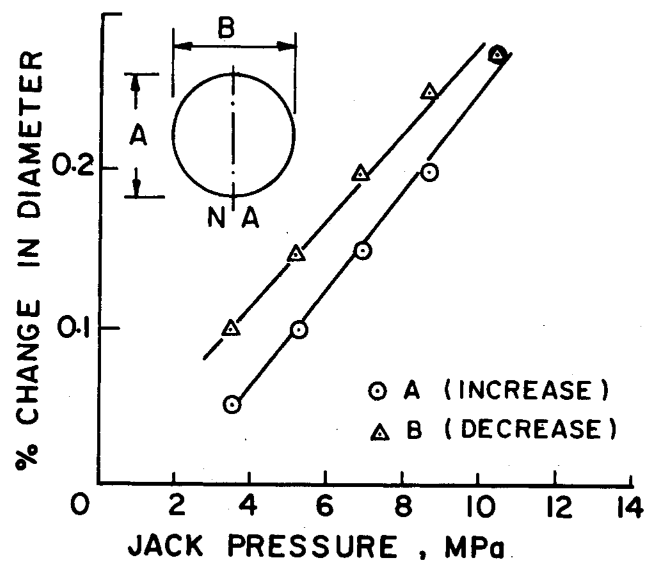

Fig. 4. Effect of bending on pipe ovality

4.0 FULL SCALE BEND TEST PROGRAM

A test program utilizing the bend test facility is currently underway. In addition to the full scale tests a study has been made of fatigue precracking the girth weld to produce an artificial defect and a series of small scale COD tests have also been made.

4.1 COD TESTING

To establish the tolerable flaw parameter $\bar{a}_{MAX}$ a series of Crack Opening Displacement (COD) tests have been made. Small scale specimens have been machined from the test pipe to a width of 10 mm and a depth of 10 mm and have been tested according to BS 5762: 1979 [9] with a crack depth of 3 mm. The specimens were tested with the crack notch positioned on the internal surface of the pipe, perpendicular to the pipe axis. To date testing has been made over a temperature range of -45°C to 25°C, the results being shown in Fig. 5.

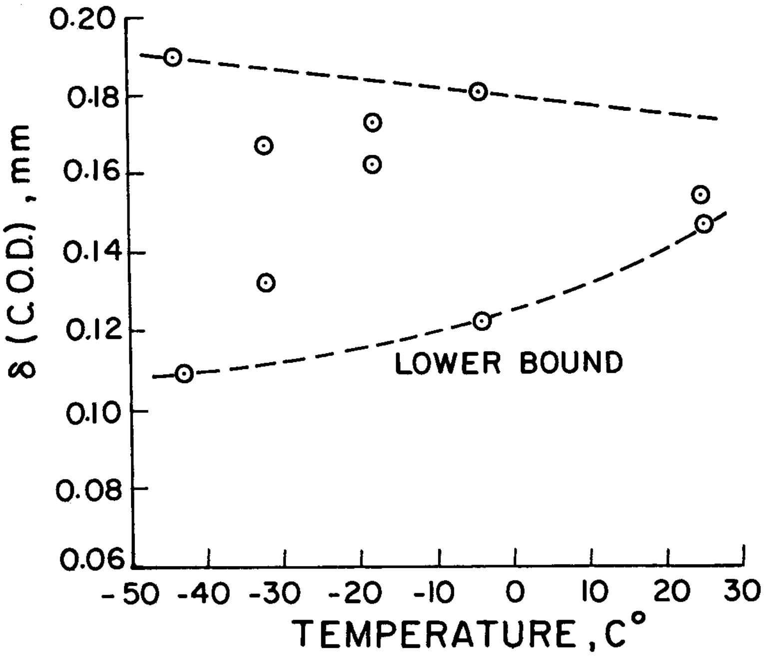

Fig. 5: C.O.D. versus temperature for test pipe.

For a defect in the pipe the flaw parameter $\bar{a}_{MAX}$ can be expressed in terms of a, the defect depth and ℓ, the defect length. For the initial test series of pipe it is proposed to use an 'a' of 50% of the wall and an $a/\ell = 0.1$. Taking an upper bound value of $\delta_c = 0.18$ mm (Fig. 5) gives a failure strain in an elastic-plastic mode of 3200 μstrain for 11.4 mm wall pipe. However it is known that the small scale COD results will be conservative and the actual failure strain in a pipe will be considerably higher.

4.2 FATIGUE PRE-CRACKING

The program is intended to study internal surface defects oriented in a circumferential direction. Although a true weld defect would be desirable the lack of control in producing a defect of a given size led the authors to adopt a procedure for producing an artificial defect. A fatigue defect was chosen because the crack tip geometry represents a condition at least as severe as any condition expected to occur during construction or service.

Two fatigue precracking rigs have been built to fatigue extend circumferencial saw cuts on the pipe interior. The initial program is to consider defects with an aspect ratio of depth to length of .1 and depths varying from 50% to 80% of the wall thickness. Compliance with ASTM E 399-79 for fracture toughness testing requires that at least 1.25 mm of the final crack be produced through fatigue growth. Previous studies at the University of Waterloo on the growth of fatigue cracks in nuclear vessels and PMMA plastic plates have developed a technique using crack starting saw cuts. To achieve the aspect ratio desired it was decided to initiate a fatigue crack from 3 saw cuts 3.8 mm deep. Fig. 6 shows the initial saw cuts and a fatigue crack grown through 80% of the wall.

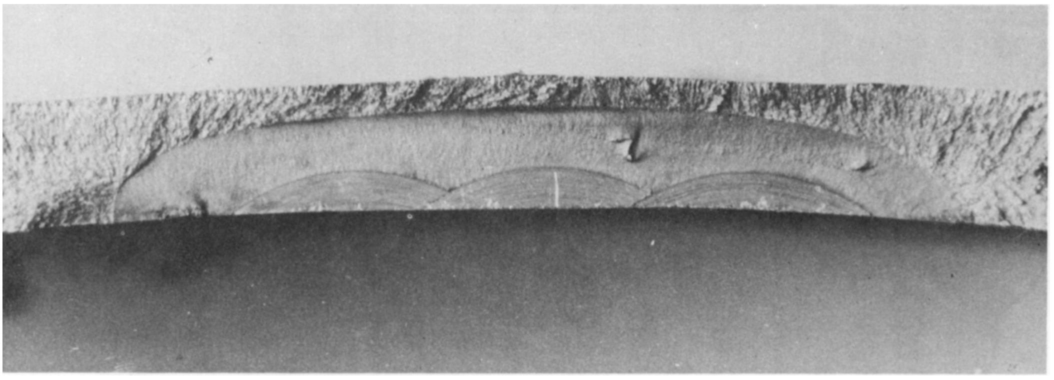

Fig. 6. Fatigue extended defect (Wall thickness 11.4 mm)

The fatigue precrack rigs consist of a loading frame surrounding the pipe allowing the application of a load to the outside of the pipe over the saw cuts with a servo controlled hydraulic actuator (Fig. 7). The interior of the pipe is supported by a diametrical member, preloaded to support defect and transfer the load across the pipe into the support frame. Considerable development was required to establish the correct position of the load applicator and support to grow a circumferential defect. While an applied load causes the desired longitudinal bending stresses, circumferencial stresses will also occur. If the circumferencial stresses are larger longitudinal fatigue cracks may develop.

Approximately 20 tests and several strain gauge studies established a 4 point bending arrangement where the load is applied 1 cm on either side of the defect and reacted by the support 8 cm on either side of the defect. The strain gauge studies and ASTM E399-79 were used to establish that the plastic zone size was acceptably small during precracking. The fatigue crack growth was continuously monitored using a clip gauge and a correlation established between the increase in clip gauge reading and the depth of crack i.e. a 17% increase in clip gauge reading corresponded to a crack growth to one half of the wall thickness. This was necessary to establish the defect size prior to testing and has proven very reliable.

4.3 TEST PROGRAM

The test program, currently underway, will be made up of two test series. The first, to study the effect of biaxial stress, consists of 4 tests, 2 with internal

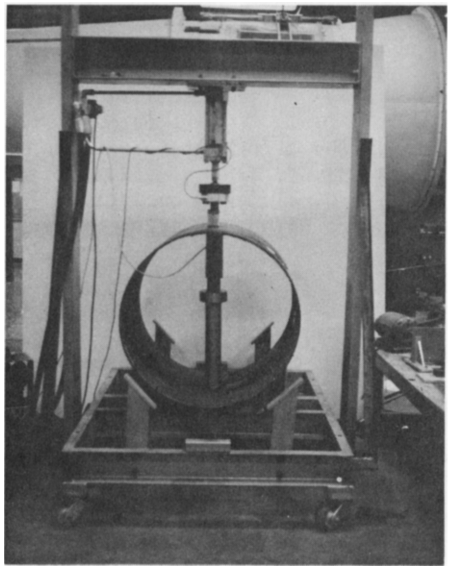

Fig. 7. Fatigue Precrack Rig

pressure, 2 without internal pressure, on plain pipe with the defect through 50% of the wall. The testing will be carried out at room temperature to allow the use of the internal pressure device.

The second series of eight tests studies the effect of defect size on the failure strain in the girth welds of pipe. Temperatures of -85°C are being used to achieve elastic fracture and -45°C to achieve an elastic plastic fracture. The minimum design temperature for gas pipeline is -45°C in northern environments.

At the time of writing 10 of the 12 planned tests have been completed. The test facility and test techniques have worked well and repeats of tests have shown excellent repeatability in duplicating defect sizes and failure strains. The results of the testing will be reported separately upon completion of the test program.

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