SIF2004 Structural Integrity and Fracture. http://eprint.uq.edu.au/archive/00000836

Design And Application Of A Drill Pipe Fatigue Test Facility

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ABSTRACT: This paper reports on the design and application of a fatigue testing facility for drill pipes. A reversed bending load is applied using a rotating drill pipe in a four point static bend arrangement with the possibility of applying an additional static tension load. Drill pipes were tested with and without static tension at different cyclic bending stresses. The stress amplitudes ranged from 30 MPa to 230 MPa on the outside surface of the drill pipe. The test results show a consistent failure mode with a circumferential crack propagating in the groove of the first engaged thread of the pin, i.e. the male section of the joint. The fracture surface as well as ultrasonic monitoring of the sample during the testing suggest that the circumferential crack growth rate is fast, and final fracture occurs within a relatively small number of cycles as soon as a through wall crack has been formed. The S-N curve collected from a total of 18 samples shows a linear trend in the logarithm of the fatigue life versus stress amplitude.

1 INTRODUCTION

The major component of any drilling operation is the drill string consisting of multiple drill pipes connected by threaded joints and providing the link between the surface of the well and the bottom of the assembly. Drill string failures are costly because of loss or damage of equipment and the time needed for complicated recovery operations. The most common reason for drill pipe failure is growth of fatigue cracks in the threaded regions due to reverse bending.

Drill pipes are manufactured to different lengths and diameters. This investigation focuses on NQ drill pipes, which are mainly used for directional exploration drilling of coal reserves. The NQ drill pipes are made from medium carbon alloy steel, which are cold drawn and subsequently heat treated to remove residual stresses. The essential drill pipe geometry and material characteristics are: outside diameter 69.85 (+0.25/-0) mm; inside diameter 60.32 (-0.25/+0) mm; yield strength 620 MPa; and ultimate tensile strength 725 MPa. Figure 1 shows the details of the tapered parallel-threaded male (pin) and female (box) ends of the pipes.

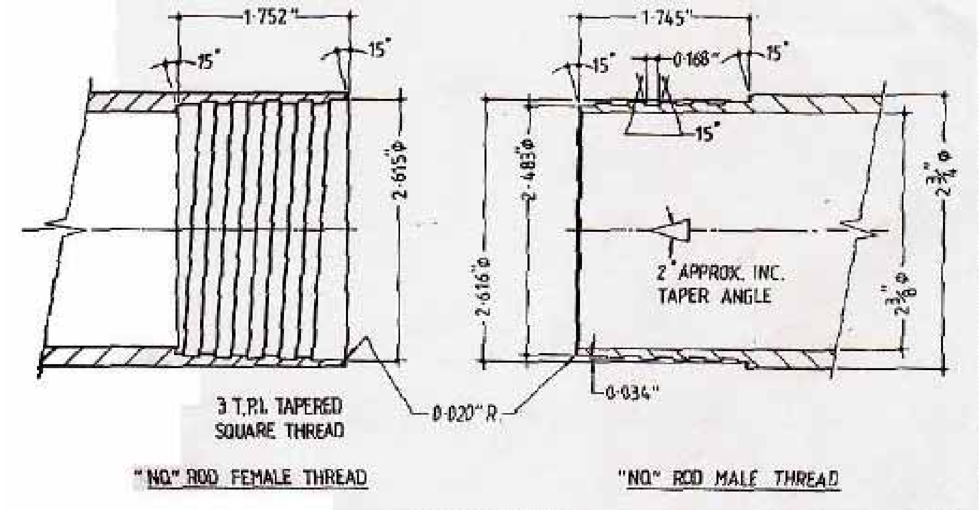

Figure 1: Details of tapered, parallel-threaded male (pin) and female (box) ends of NQ drill pipe

Drill pipes are exposed to extremely harsh environmental and loading conditions, e.g. [10]. Fatigue damage is caused when the pipe is subjected to large alternating stresses, for example when the drill pipe rotates in a curved segment (dog-leg) of the well bore, which may be the result of unintentional deviations or which are necessary for directional and horizontal wells, [4, 11]. In addition to bending, axial loads of either tension or compression are also acting, [6]. In vertical and moderate directional drilling the majority of the drill string is in tension due to the weight of the drill string and the application of bottom hole drill collars, which are used to prevent drill string buckling and excessive drill string vibrations and help providing the desired compressive force on the drill bit, [9].

This paper reports on the design and application of a fatigue testing facility for NQ drill pipes. A reverse bending load is applied using a rotating drill pipe in a four point static bend arrangement with the possibility to apply an additional static tension load.

2 EXPERIMENTS

2.1 Test Rig and Procedures

Figure 2 shows a drawing of the four point bend test rig. The main components are four roller bearings, a hydraulic bending actuator, two thrust bearings made in-house, a hydraulic tension actuator and an AC motor controlled pulley belt transmission system.

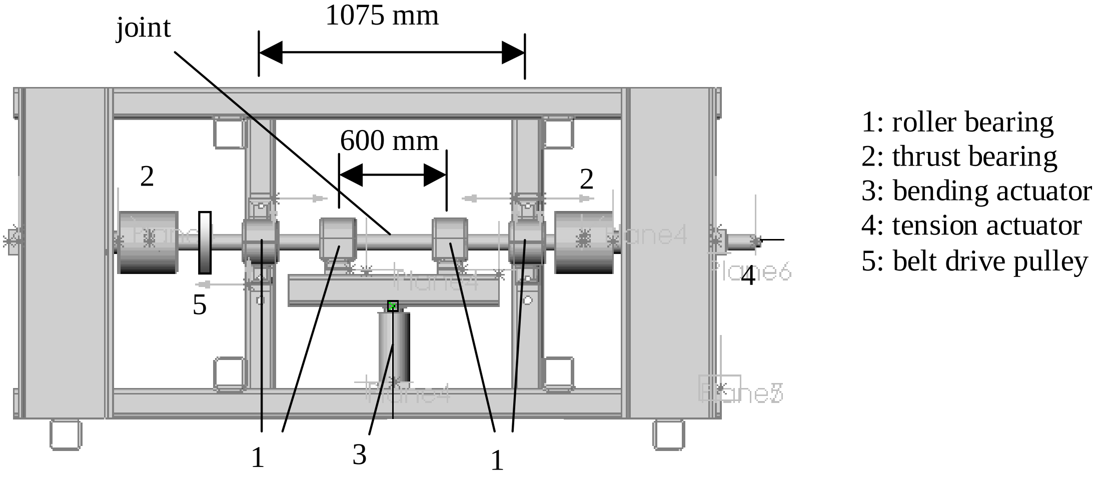

Figure 2: Drawing of four point bend test rig with major system components and dimensions

The facility is designed to operate at speeds up to 1000 rpm (corresponding to 1.44 million cycles in 24 hours). The number of cycles are measured using a photo-transistor sensor, and rotary end switches monitoring the displacement of the inner roller bearings are connected to the AC motor controller to automatically stop the experiment if excessive deflections occur. The design load for bending is 32 kN, which corresponds to maximum reverse bending stress amplitudes of 261 MPa at the outside of the drill pipe in the region of the joint. The tension actuator can create static loads of 12 kN enabling the superposition of static normal stresses of up to 12 MPa.

In service, a so-called make up torque is applied to the threaded joints, which has to be larger than the torque applied to the drill string during operation. As a result, the joints are preloaded; the pin in tension and the box in compression. The make up torque has a considerable effect on the stress distribution in the threaded joint, [12], which, in consequence, changes the fatigue behaviour of the drill pipe joint. Hence, a special loading apparatus was constructed, which enables the application of a controlled make up torque. According to American Petroleum Institute recommendations, [1], the specimens were preloaded by a torque, which creates a stress level at the outside of the pipe of 60% of the material's yield strength.

Commissioning tests of the system were performed using drill pipes instrumented with strain gauges. As an example, Figure 3 shows the results of bending and axial load calibrations and highlights the excellent agreement between the predicted and measured axial strains.

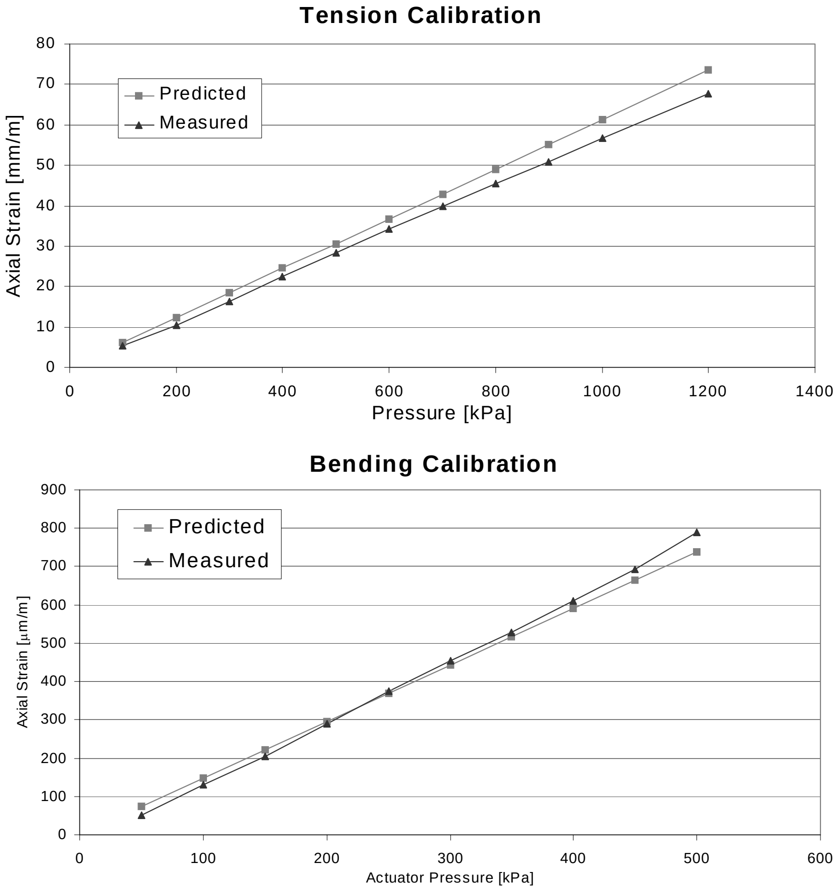

Figure 3: Results of a) bending load and b) tension load calibration

2.2 Fatigue Testing

A total of 18 fatigue experiments were conducted. The test plan was established based on a standard method to estimate the slope section of the S-N curve, e.g.[7]. The typical service life of a NQ drill pipe is in the order of 3000 hours, which corresponds to 18 million cycles, if the drill string rotates at a speed of 100 rpm. However, not all of these cycles are to be accumulated while the joint is passing through doglegs where reverse bending may create fatigue damage. As a result and based on manufacturers specifications, 3 million cycles were defined as an initial safe life limit for NQ drill pipes. Table 1 shows a summary of the experimental parameters and test results. The tests were carried out at rotational speeds between 500 and 800 rpm.

Test	Maximum Stress [MPa]	Mean Stress [MPa]	Speed [rpm]	Cycles	Failure
1	236	0	550	656	complete break
2	236	0	550	4420	complete break
3	197	0	500	2280	complete break
4	157	12	630	8238	complete break
5	148	0	500	13408	complete break
6	118	12	630	46180	complete break
7	118	0	500	20524	complete break
8	98	12	630	133214	complete break
9	98	12	800	112661	complete break
10	98	12	800	279719	complete break
11	98	12	800	129602	complete break
12	98	0	550	204610	complete break
13	98	0	550	178518	complete break
14	79	12	630	424380	partial break
15	79	12	630	389558	complete break
16	59	12	630	1043266	partial break
17	59	12	630	1214349	partial break
18	39	12	630	3000000	run out

Table 1: Summary of experimental parameters and test results

3 RESULTS AND DISCUSSION

In all cases of complete specimen failure the threaded pin joint completely broke off at the last engaged thread as shown in Figure 4. The crack initiated on the outside surface of the threaded joint, in the corner of the last engaged parallel thread as shown in Fig. 1. It was found that the crack consistently initiated between 90º and 180º from the end of the helical thread. The box end of the joint sustains no visible damage on the outside surface of the joint. To inspect the inside surface of the failed specimens, the box joint was sliced along the axis of the drill rod. Once again there was no visible damage in this section of the joint. Based on the structure of the crack surface it is suggested that the crack initially propagates through the thickness of the pin joint and subsequently follows the corner of the square thread in both circumferential directions. Once the crack has reached the critical length, the remainder of the helical path is closed by plastic tearing in the direction of maximum shear, i.e. under 45º to the longitudinal axis of the drill rod. Based on the results of continuous non-destructive monitoring of the drill pipe during fatigue testing using structural wave ultrasonic techniques, it appears that this final stage of the fatigue process occurs over a very limited number of revolutions, finishing with closing the 360º crack path by bridging the distance between the first and second thread with a final axial separation crack.

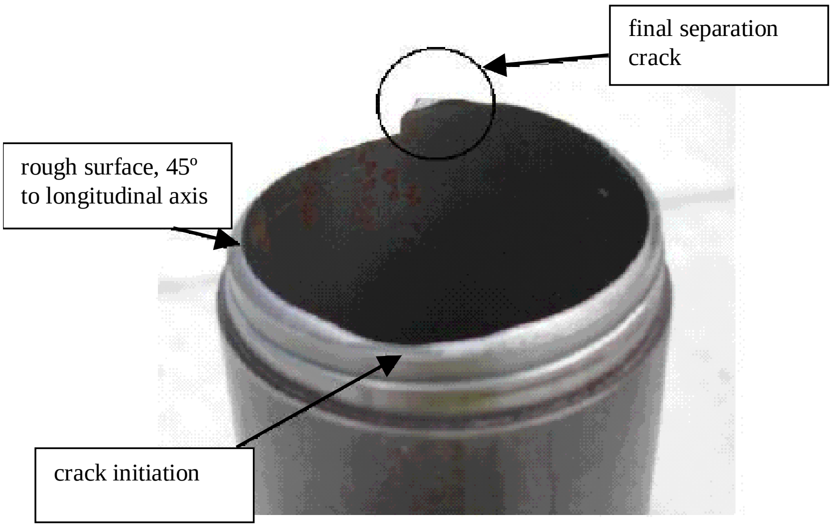

Figure 4: Fatigue failure surface in threaded pin joint of the specimen.

Not all tests resulted in full fracture through the pin joint. In some cases the test was terminated before the threaded joint had completely separated. The cause being the activation of the rotary end switches due to excessive deflection of the drill pipe. Once the crack had propagated to a sufficient circumferential length, the open crack created considerable deflection, which in turn activated the stopping mechanism. Three drill pipes tested at lower stress levels failed in this mode. Once the drill pipes were removed from the testing facility and the make up torque released, a circumferential crack in the pin thread was clearly visible, which extended between 70% to 80% of the length of the first engaged thread.

Figure 5 shows the S-N diagram produced from the data points listed in Table 1. The first thing to note is the relatively small number of cycles needed to create fatigue failure of NQ drill pipes under reverse bending loads. Even for maximum stress levels of 100 MPa, which are very moderate compared with the material's strength limits, the drill pipe joint consistently fail below 300,000 cycles. Recommendations based on earlier studies, [2, 3, 5], use maximum allowable dog-leg severities measured in degrees per length to define operational limits to avoid drill string fatigue failures. A simple relation allows to convert dog-leg severities to stress amplitudes and it turns out that the recommended upper limits of dog-leg severities correspond to reverse bending stress amplitudes of approximately 150 MPa, which is clearly above the values resulting in early fatigue failure in the current investigation. A possible explanation is the large stress concentration factor that exists in square threaded joints. Finite element analyses of tapered threaded joints show that the highest stress concentration is in the last engaged thread of the pin joint and a stress concentration factor of 15 should be included [8, 12]. If this factor is applied to the nominal stress at the outside surface of the drill pipe and 30 MPa are assumed to be the endurance limit for 1 10^7 cycles, the effective fatigue stress is 450 MPa, which is in good agreement with reverse bending fatigue limits for alloy steels with tensile strengths of approximately 700 MPa.

The limited number of tests does not allow to draw any final conclusions of the influence of a superimposed static tension load corresponding to the suspended weight of a 180 m long drill string has no measurable effect on the fatigue life. This is expected since the corresponding mean stress of 12 MPa is small compared to the alternating stress.

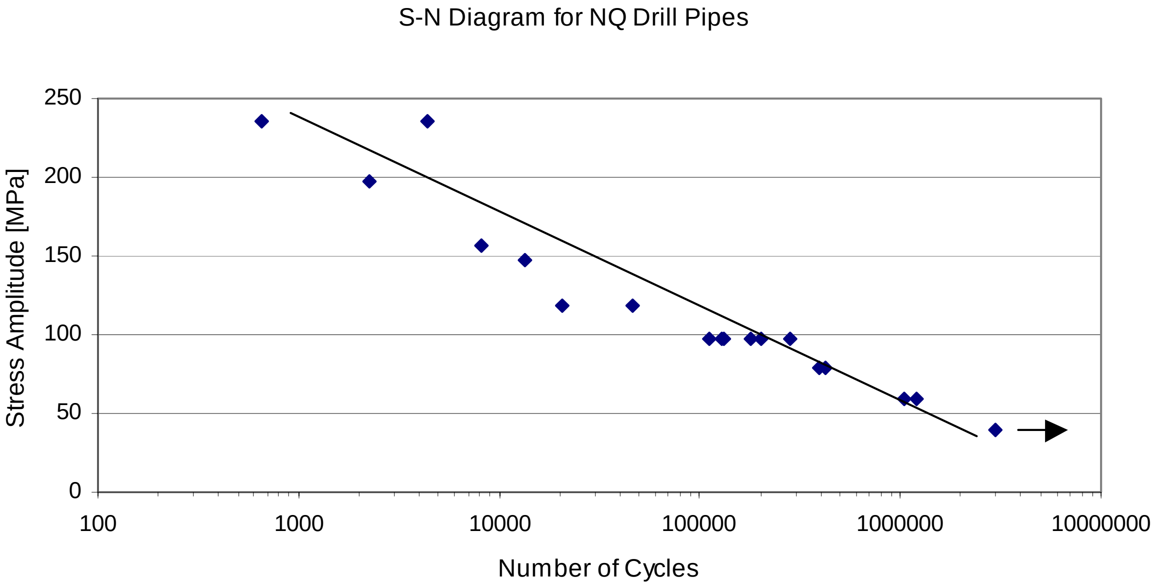

Figure 5: S-N diagram of NQ drill pipes

4 CONCLUSIONS

This paper has reported on the design and application of a unique fatigue testing facility for NQ drill pipes. The test rig allows the application of combined reverse bending and static tension loads to the threaded joint of NQ drill pipes. The results of the fatigue tests show that:

- single mode of failure exists, which is in agreement with predictions based on finite element analysis of pre-loaded tapered threaded joints. The crack initiates at the base of the last engaged thread of the pin joint. Once the crack has propagated through the thickness, two cracks propagate in opposite directions around the circumference of the joint.
- fatigue failure occurs at low nominal stress levels. This is due to the considerable stress concentration in the pre-loaded thread. The effective stress levels agree well with fatigue limits predicted for alloy steels with similar tensile strength properties.
- there exists a linear relation between the nominal stress amplitude and the logarithm of the number of cycles to failure in a stress range between 30 MPa and 230 MPa.
- the superposition of a static tension load corresponding to the suspended weight of a 180 m long drill string has, as expected, no measurable influence on the fatigue life of the drill pipe specimens.

ACKNOWLEDGEMENT

The authors thank Jonathan Ramm, Asanka Basnayake and Law Tian We for collecting some of the fatigue test data, the CRC Mining (former CRC for Mining Technology and Equipment) for providing the Master of Engineering scholarship for Alex Berezovski, and Barry Allsop and Bob Gammie for their technical support in the design of the drill pipe fatigue test rig.

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