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Inspection and testing of failed tow wire rope from tug *ALP Forward*

FINAL REPORT

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Summary

This report presents the findings of a study undertaken on a wire rope being used as the towing wire on *ALP Forward* to tow the *Transocean Winner* between Norway and Malta when it parted in heavy weather on 8th August 2016. The platform *Transocean Winner* subsequently ran aground at the Isle of Lewis.

The **MAIB** wished to understand why the wire rope failed and why it failed where it did.

Initial work was undertaken which inspected sections of the wire rope from the following locations along its length:

- a 5 m sample from the drum ('drum sample') which had not previously been deployed and was considered to be representative of the rope's new condition;
- Approx. 20 m samples from each side ('tug side' and 'rig side') of the main wire rope failure;
- a 20 m sample from adjacent to the socket which connected the wire rope to the towing bridle ('bridle sample').

Initial visual inspection of the tug side sample and bridle sample found numerous shear type wire breaks in the outer strand outer wires. These were located in the valley positions between outer strands and thought to be caused by heavy contact between the strands.

Full dismantling inspection and testing was made of selected 1 m long samples from each of the drum, tug and bridle sections. Testing of wires from the drum sample indicated that the rope as purchased was manufactured from wire stock with mechanical properties which satisfied the requirements of API 9A.

The tug and bridle samples were in similar condition, and considered to be representative of the condition of the length of wire rope deployed and so of that at the main failure at the time of the incident:

- The lubricant level was low;
- The outer strands were covered in a light coating of corrosion;
- There was very little protective galvanising remaining on the exposed surface of the wires;
- Several outer strand outer wire breaks were noted along the length; and,
- The independent wire rope cores were in very poor condition, each with over 100 wire breaks on the 1 m samples.

It is impossible to know when all this degradation occurred, but difficult to see it all being as a result of the job which *ALP Forward* was engaged at the time of the incident.

Tensile breaking load tests were undertaken on whole rope samples from the drum, tug and bridle sections. The results of these tests showed that the strength of the drum sample was down by about 7% on the originally measured breaking strength, whilst the tug and bridle samples were both over 20% down on as new.

The nature and distribution of the wire failures in the breaking load samples was very similar to the main failure (tug side sample). The outer strand outer wires had predominantly failed in shear, whilst the outer strand inner wires had failed in classic cup and cone type fractures. (The rig side sample main failure was not inspected as it had suffered extensive abrasion damage dragging along the seabed post failure.)

A consideration of the fatigue performance of the six strand rope indicated that during the storm the wire rope would have accumulated fatigue damage which would contribute to degradation.

Analysis of catenary behaviour indicated that under high tensions the wire rope would be reliant on elastic stretch to accommodate any sudden displacement caused by waves, and that very high tensions could easily be produced by relatively small displacements.

It is concluded that the wire rope was weakened by accumulated damage during the storm and ultimately failed by tensile overload in its weakened state.

Contents

Glossary

ABL	(measured) Actual Breaking Load
d	Rope nominal diameter
d_w	Wire diameter
F_{min}	Minimum breaking load
IWRC	Independent Wire Rope Core
Lay length	the axial length over which a wire (or strand) make one helical revolution about a strand (or rope).
RHO	Right Hand Ordinary lay

1 Introduction

TTI Testing (**TTI**) has been contracted by the Marine Accident Investigation Branch (**MAIB**) for assistance in determining the cause of a wire rope failure (**MAIB** Reference number 4/3/144). The wire rope was being used as the towing wire on *ALP Forward* to tow the *Transocean Winner* between Norway and Malta when it parted in heavy weather on 8th August 2016. The platform *Transocean Winner* subsequently ran aground at the Isle of Lewis.

The **MAIB** seeks to understand why the wire rope failed and why it failed where it did. Specifically:

- The condition of the wire rope where it failed and at other selected points
- The implications of its condition on serviceability at the time of failure
- The mechanism of the wire rope's failure
- The load on the wire rope when it failed
- The load the wire rope would have failed at had it been new

As a secondary issue, the emergency towing arrangement on *Transocean Winner* included a steel pennant, connected at one end to the rig and at the other to a floating polypropylene (PP) pick-up rope. The PP rope was in turn connected to a messenger line, and the outboard end of the messenger was connected to a wave-rider (Norwegian buoy). When *Transocean Winner* was examined after grounding, a section of the messenger line and buoy were no longer present. The **MAIB** wished to understand how the messenger line came detached from the buoy. In the absence of other evidence, this could only be determined by a thorough examination of the end of the messenger line.

This document presents background information relevant to the study, and describes the initial inspection and testing of the sections of wire rope which were sent to **TTI Testing**, Wallingford. Results of the tests are presented along with a discussion of the results to address the questions raised above.

The examination of the pick-up rope and messenger line is covered in a separate report.

2 Main tow wire rope

The wire rope was a nominal Ø77 mm six strand wire rope with Independent Wire Rope Core (IWRC) Right Hand Ordinary Lay rope manufactured in 2013 by Usha Martin in accordance with API 9A:2011 [**1**]. Table 2.1 list the main parameters of the wire rope where known, and the wire rope inspection certificate is presented in Appendix A. Figure 2.1 presents a cross section of the construction showing the arrangement of the layers of wires in the wire rope.

Parameter	**Value**
Nominal Diameter [mm]	77
Measured Diameter (off tension) [mm]	78.46
Measured lay length (off tension) [mm]	534
Rope Length [m]	1600
Construction	Super Titan 6 × 37 class + IWRC, RHO
Wire Finish	Galvanised
Lubricant	D / Bitumen Lubricant
Minimum Breaking load (F_{min}) [kN / tonnes]	4751 / 485
Measured (Actual) Breaking load, ABL [kN / tonnes]	4847 / 494.1
Manufacturer	M/S Usha Martin Ltd., Ranchi, India
Date of initial inspection	28th June 2013
Date of last inspection	5th July 2016

Table 2.1: Main properties of the failed towing rope.

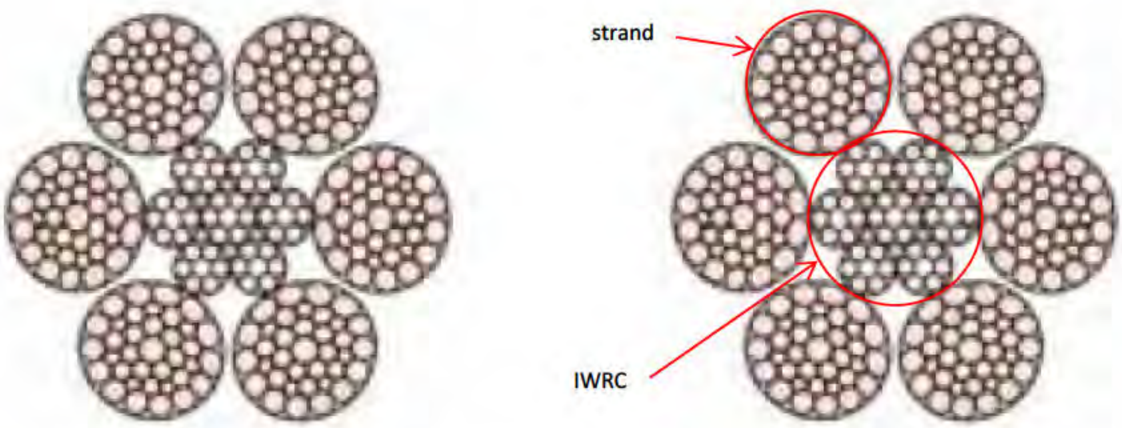


Figure 2.1: Typical 6 × 37 + IWRC 'Super Titan' wire rope cross-section [from **2**], and terminology.

Table 2.2 presents data from the individual wire tests for the wires in the main load bearing strands of the rope.

Wire diameter, d_w	Tensile strength (Average)	Bend (Average)	Torsion (Average)	Weight of zinc coating (Average)
[mm]	[N/mm^2]	[-]	[turns /100 d_w]	[g/m^2]
4.39	2164	N/A	13	161
2.73	2096	N/A	23	142
3.53	2128	N/A	17	146
3.62	2075	N/A	16	146
4.81	2087	N/A	12	163

Table 2.2: Average wire properties for the main load bearing outer strand wires (from Usha Martin Inspection Certificate - See Appendix A).

3 The towing arrangement and sample location

Figure 3.1 presents a schematic diagram of the towing arrangement at the time of the wire rope failure. It is understood that the wire rope was attached to *Transocean Winner* by means of a triangular plate and twin legged bridle in turn attached to two of the platform legs (Figure 3.2). The total scope of the tow varied as the line was paid out and hauled in during the voyage. At the time of the tow line failure, approximately 740 m of line was paid out [**3**].

The wire rope failed load about 160 m clear of the rig Winner. The load at failure is unknown, but loads of 180 - 220 tonnes were being recorded at about that time (04:21 UTC+1 on 8th August 2016) [**3**].

Following the wire rope failure the **MAIB** conducted a preliminary examination of the tug side of the failure (which was readily recovered). The following samples were identified/taken from the failed wire rope for further examination and testing:

- Approximately 20 m of wire rope from the failure point towards *ALP Forward*. This sample will be referred to as the ***'tug side sample'***. This length was chosen to include all the wire rope in the vicinity of the break where strand/wire failures were visible (see Figures 3.3 and 3.4).
- A further 5 m section of the wire rope was taken from the end of the wire rope secured to the drum (the ***'drum sample'***). This sample was removed from the *ALP Forward* once it had returned to Rotterdam. It was shipped to TTI Testing separately to the two samples comprising the failure which were shipped from Stornoway. The drum sample was intended to provide an un-damaged section of wire rope for comparative analysis.
- Once *Winner* had been salvaged, a length of approximately 20 m of the tow wire leading to the breakage point was taken (the ***'rig side sample'***).

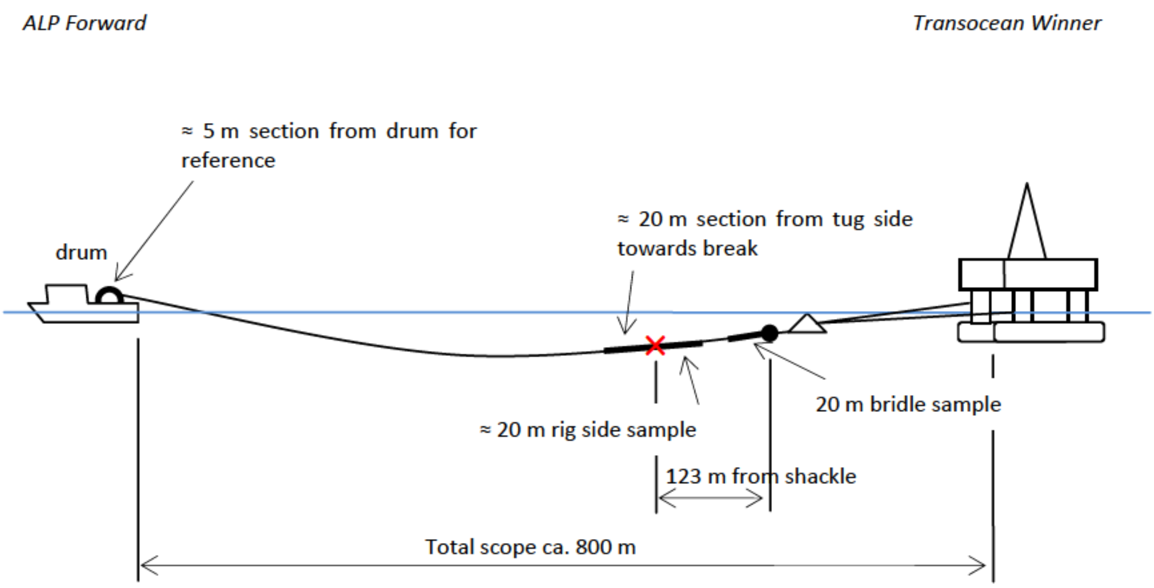


Figure 3.1: Diagram of the tow arrangement at the time of the wire rope failure and samples taken for inspection. (Position of failure of the wire rope marked with an '×').

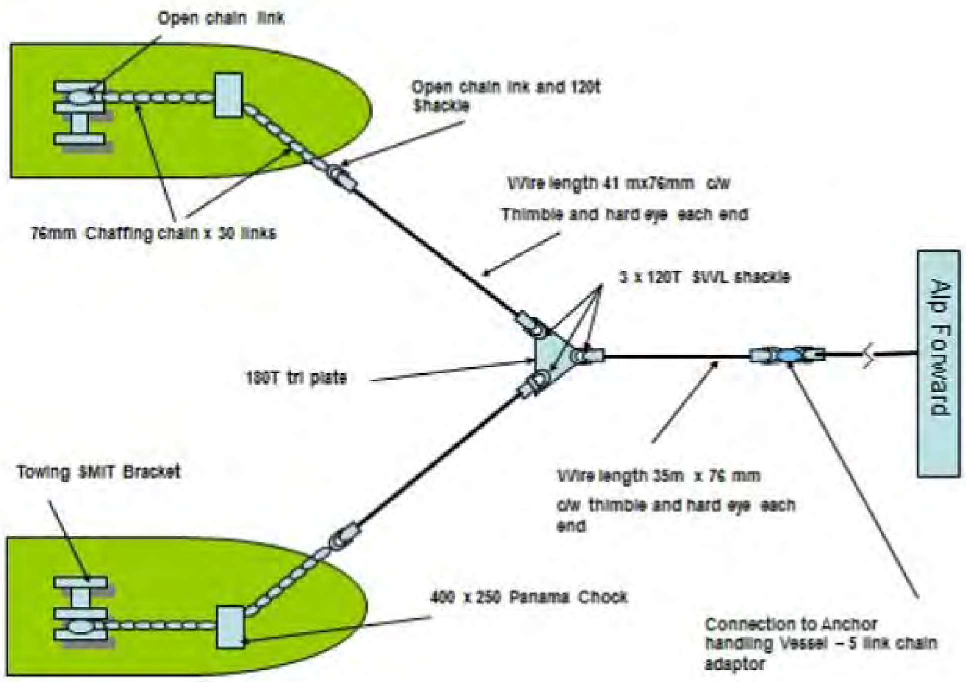


Figure 3.2: Schematic diagram of the bridle arrangement connecting *Transocean Winner* to *ALP Forward*.

Figure 3.3: View on failure of 77 mm wire rope (*tug side*) (Photograph supplied by **MAIB**).

Figure 3.4: *Tug side* sample taken for inspection: 20 m from the failure towards the tug *ALP Forward* (Photograph supplied by **MAIB**).

4 Delivery of samples

4.1 Delivery of the drum sample

The drum sample was delivered to **TTI Testing** from Rotterdam in a sturdy wooden crate which had been made especially for the sample (Figures 4.1 and 4.2).

Figure 4.1: Drum sample as received at TTI Testing.

Figure 4.2: Drum sample as received at TTI Testing with crate lid fully removed.

4.2 Delivery of the tug side and rig side samples

The tug side and rig side samples were transported to TTI Testing in a locked 10' container (Figure 4.3). The two samples were coiled and separated from each other by sheets of 10 mm plywood and tarpaulins (Figures 4.4 and 4.5).

The samples were carefully removed from the container in turn and laid out on the laboratory floor to permit an initial inspection (Figure 4.6).

Figure 4.3: Container with tug side and rig side samples as received at TTI Testing.

Figure 4.4: Container opened to show tug side (top) and rig side (bottom, wrapped) as received.

Figure 4.5: Rig side sample in container (unwrapped).

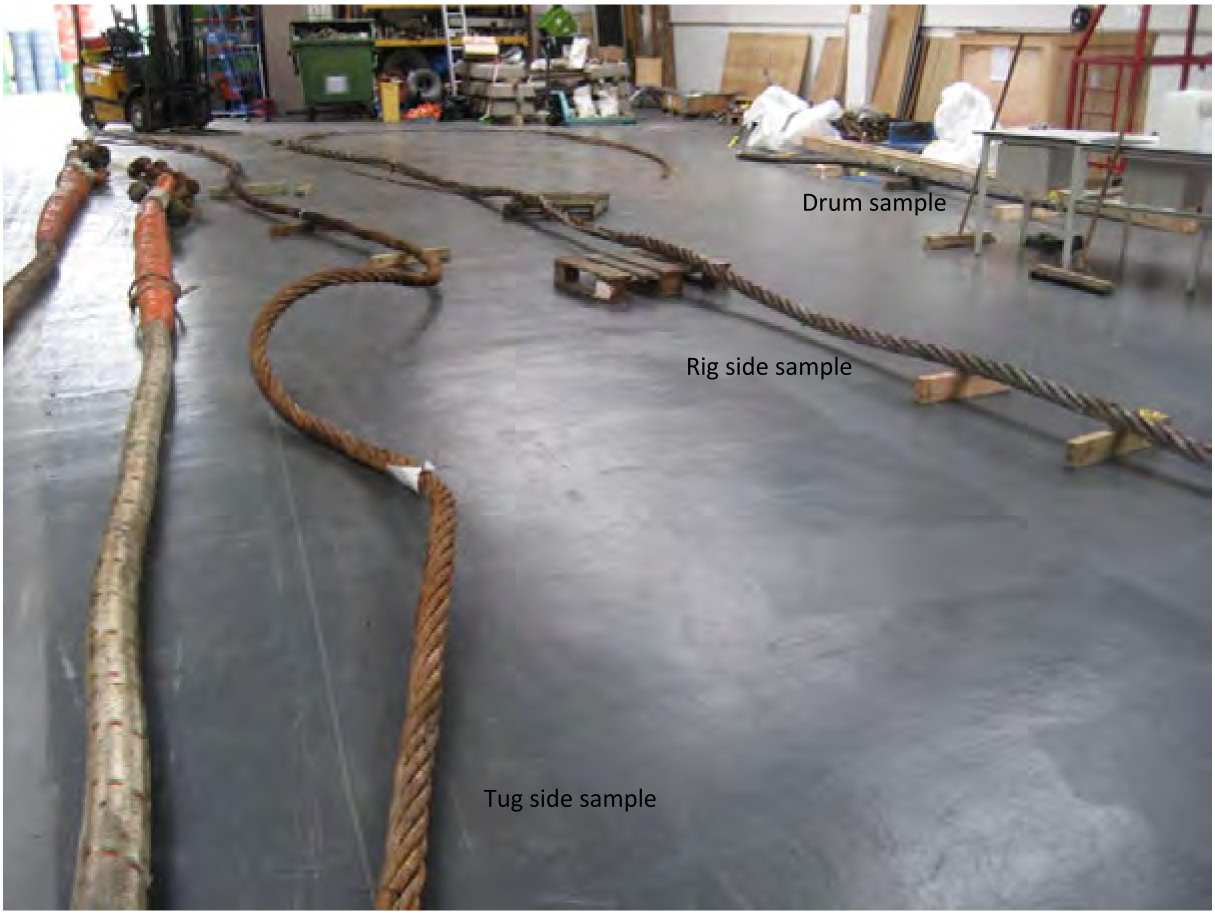


Figure 4.6: Samples laid out in TTI Testing laboratory for initial inspection.

5 Initial inspection of samples

5.1 Initial inspection of drum sample

Figure 5.1 shows the general condition of the drum sample as received. Generally the sample was well lubricated particularly in the outer strand valleys. Where present the lubricant was glossy and black in appearance, and as new. There were also some grey deposits of what were thought to be mud or silt. It is not known at what stage these were deposited on the wire rope. Superficial corrosion was noted on the surface of the wires.

Mid-length along the sample was found an area of crushing damage on one of the strands. Whilst not ideal, it is thought that this damage would not adversely affect the breaking strength of the sample as the damage should 'pull out' under the high loads.

Figure 5.1: General condition of the drum sample as received.

Figure 5.2: Area of crushing damage found on the drum sample (mid-length).

5.2 Initial inspection of tug side sample

The tug side sample was laid out and measured at 19.2 m overall length. Measuring from the cut end of the sample the first strand failure of the main failure was measured at 10.2 m (Figure 5.3). Over the next lay-length or so this strand pulled into the middle of the wire rope, displacing the IWRC so that it was not obvious that it had failed there.

Where exposed, the IWRC appeared to be in poor condition. Multiple wire breaks were observed, the core was dry and lacking in lubrication and corrosion had begun (Figure 5.4).

At 12.96 m a pair of servings were noted. It is assumed that these were put in place by personnel removing the failed sample for examination (Figure 5.5).

Finally, Figure 5.6 shows the failed end of the tug side sample. The IWRC failed at approximately 18 m from the cut end, and the remaining five strands at distance 18.5 m, 18.7 m (2 off) and 19.2 m (2 off). A more detailed analysis of the failure will be reported in Section 11.

Figure 5.3: Strand failure noted at 10.6 m from cut end on tug side sample (started at 10.2 m).

Figure 5.4: IWRC displaced from the centre of the wire rope at 12.5 m from cut end on tug side sample.

Figure 5.5: Seizing wire on wire rope measured at 12.96 m from cut end on tug side sample.

Figure 5.6: Failure of IWRC and five strands over a distance 18.0 - 19.2 m from the cut end on tug side sample.

Figures 5.7 - 5.9 show typical views of the wire rope on the 10.2 m section between the cut end and the start of the main failure. These views provide information on the general condition of the wire rope at the time of the incident.

It is immediately noted that the lubricant between the strands is missing, the protective galvanising seems low or lost, and the wires (the outside of the wire rope) are covered in what appears to be superficial corrosion. Wire breaks were noted distributed along the 10 m length, both along and around the wire rope circumference. In all 40 visible breaks were counted (there may well have been more), all of which initiated at the inter-strand contact region of the wire rope and appeared to be shear type in nature. Beyond 10 m from the cut end there were many more wire breaks.

A more detailed assessment of the condition of the tug side sample was made on the full inspection of a 1 m sample, including mechanical tests on the wires.

Figure 5.7: Outer strand wire break (valley) measured at 1.4 m from cut end on tug side sample.

Figure 5.8: Two of six outer strand wire breaks measured at 2.0 m from cut end on tug side sample.

Figure 5.9: Two outer strand wire breaks measured at 5.6 m from cut end on tug side sample.

5.3 Initial inspection of rig side sample

The rig side sample was uncoiled and measured at 23.2 m overall length, although 9 m of that length comprised the remains of the single strand which was noted to have failed at 10.2 m on the tug side sample.

Comparison of Figures 4.4 and 4.5 shows that the tug side and rig side samples appeared quite different. (It is noted that the samples had been treated or coated post recovery to preserve the evidence which may contribute in part to this disparity.) The tug side sample had a uniform coating of corrosion, whilst the rig side sample had marked shiny patches on the crown positions of the strands, the most heavily affected area being in the first 4 m or so from the cut end. Figure 5.10 shows a general view of the sample near the cut end. It may be seen that there are valley wire breaks as were noted on the tug side sample, but also significant abrasion damage (Figure 5.11).

The lack of corrosion on the surface of the abrasion suggests that it is very recent. It must be considered possible that this damage (the abrasion) was caused to the wire rope after the failure of the tow. Given the position of the main failure along the wire rope the failed end of the wire rope would have dragged along the seabed for some distance (≈ 3 miles) as the rig drifted. The nature of the seabed is not known, however small pieces of stone were found between strands in positions along the length of the sample (see for example, Figure 5.12).

The suggestion that the abrasion damage occurred post to failure is supported by the condition of the IWRC which had displaced from the centre of the wire rope construction at 5.7 m from the cut end (Figure 5.13).

Figure 5.14 shows the failed end of the sample. The end of the IWRC was measured as 12.1 m from the cut end. It is therefore quite possible that a short section is missing. This is not surprising given the condition of the core noted in other positions along the wire rope which showed numerous wire breaks.

Figure 5.10: General condition of the wire rope about 1.1 m from cut end of rig side sample.

Figure 5.11: Significant abrasion on the surface of the outer wires 2.0 m from cut end of rig side sample.

Figure 5.12: Small pieces of stone noted trapped in the wire rope at 5.6 m from cut end of rig sample.

Figure 5.13: Abrasion (and wire breaks) noted on the displaced IWRC at 7.2 m from cut end of rig sample.

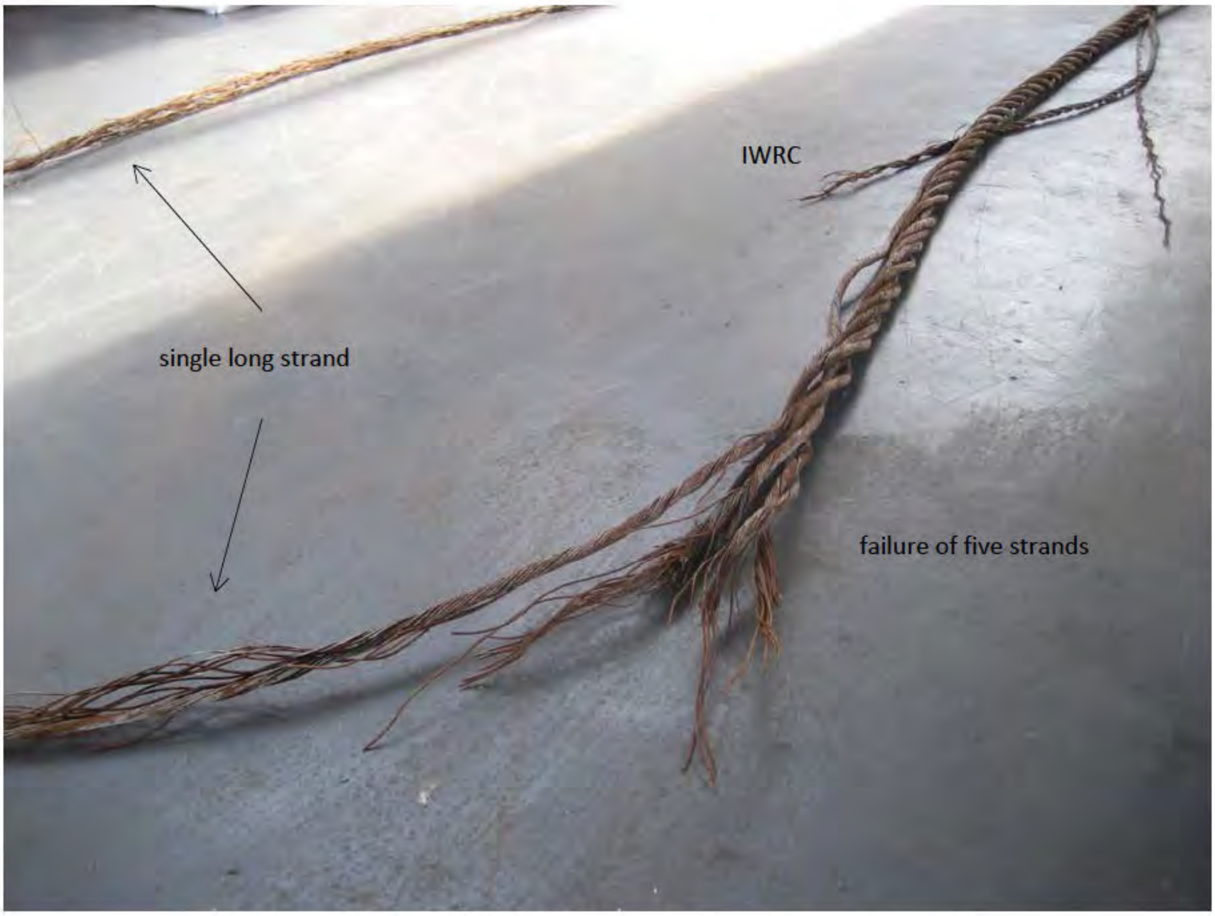


Figure 5.14: General view on main wire rope failure (rig sample).

6 Initial cutting schedule

An initial cutting schedule was drawn up based on the on the preliminary inspection of the three samples which were supplied (Figure 6.1).

6.1 Cutting schedule for drum sample

- A 1 m section was taken from the end of the drum sample for a full strip down inspection and mechanical tests on representative wires (the strip down inspection).
- The remaining 4 m length was sent to **Mennens** for whole wire rope breaking strength measurement. It is noted that this section included the area with crushing damage noted in §5.1, but it was not thought that this would affect the strength measurement. (In any case, as the damage was mid length on the sample it was impossible to avoid.)

6.2 Cutting schedule for tug side sample

- The sample for break load was taken as the first four meters from the cut end.
- A further 1 m sample for the strip down inspection and mechanical tests on representative wires was taken at 8 m - 9 m from the cut end. This section was chosen as it was close to the start of the main failure whilst avoiding major disturbance to the construction.

6.3 Cutting schedule for rig side sample

The rig side sample was cut at 4 m and 5 m from the cut end. This provided samples for the breaking load and strip down inspection. However, as discussed in §5.3 above, it seemed unlikely that this sample was representative of the wire rope condition at time of the failure.

Discussion with the **MAIB** identified another section of the wire rope which was available - a section of rig side wire rope from near to the bridle which would have experienced the same loading, but not have dragged on the sea bed. This sample was termed the 'bridle sample'.

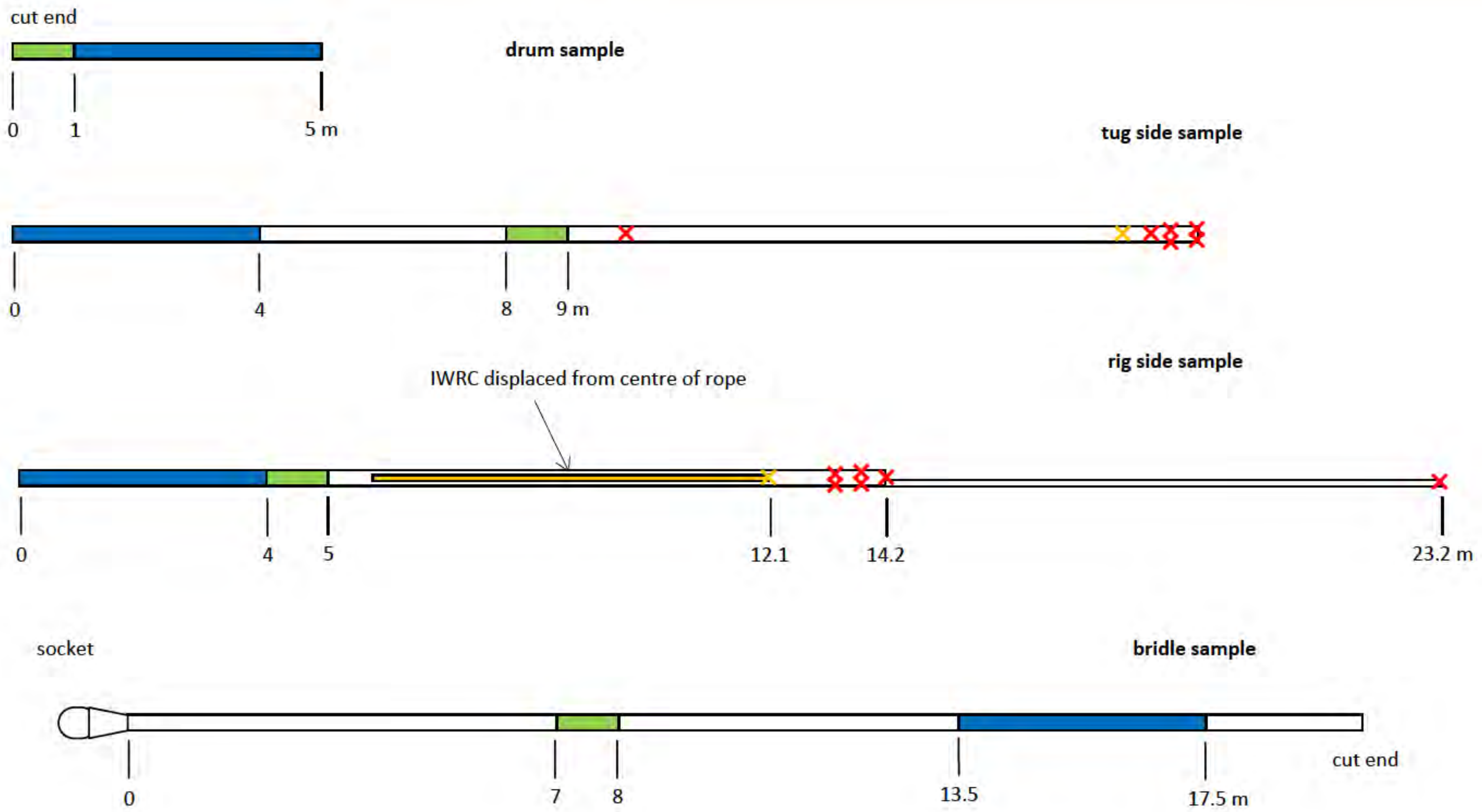


Figure 6.1: Summary of main sample features and cutting schedule (× marks approximate position of IWRC or strand breaks).

7 Delivery of bridle sample

The bridle sample was delivered to **TTI Testing** from Montrose coiled in a 10 ft half height container, protected by a tarpaulin. It was carefully removed from the container and placed in the laboratory for inspection (Figure 7.1).

Figure 7.1: Bridle sample as received at TTI Testing complete with closed spelter socket.

8 Initial inspection of additional sample

8.1 Initial inspection of bridle sample

Figure 8.1 shows the general condition of the bridle sample as received. In general terms the sample appeared to be in the same condition as that of the tug side sample (compare with Figures 5.7 - 5.9):

- the lubricant on and between strands was missing;
- the protective galvanising seems low or totally lost, and the surface of the wire rope is at the point of onset of corrosion.

Wire breaks were observed along the sample (40 were counted over the 20 m length). Two groups of wire breaks were observed at 15.2 m (eight), Figure 8.2, and at least six at 16.5 m, Figure 8.3. (All distances measured from the front of the socket face.) In all eighteen wire breaks were counted over a 30d[1] length (2.31 m).

As with the tug side sample, all the observed wire breaks had initiated at the inter strand contact position. Wire breaks in this position can be very difficult to identify, and it is quite possible that there are many more in this section of the wire rope.

Figure 8.1: General condition of the bridle sample as received (7.1 m).

Figure 8.2: Group of at least eight wire breaks noted at 15.2 m on the bridle sample.

[1] d is the nominal diameter of the rope and used as a characteristic length in the definition of discard criteria.

Figure 8.3: Group of at least six wire breaks noted at 16.5 m on the bridle sample (the blue paint is from the shipping container).

8.2 Proposed cutting schedule for bridle sample

It was considered that the bridle sample was a fair representation of the condition of the wire rope at the time of failure. Reference to the main tow-wire log [**4**] indicates that all the recorded tow miles were made with at least 200 m of wire rope paid out.

The following cutting schedule for the bridle sample was employed, based on the preliminary inspection (see also Figure 6.1).

- A 1 m length at 7 m - 8 m for a full strip down inspection and mechanical tests on representative wires (the strip down inspection). This left a 7 m sample including the socket should there be any wish to conduct a break strength measurement on the fitting/wire rope assembly.
- A 4 m length at 13.5 m - 17.5 m which was sent to Mennens for whole wire rope breaking strength measurement. It is noted that this section included the 18 wire breaks over a length of 30d noted in §8.1 above.

9 Wire rope breaking strength measurement

9.1 Test equipment

The tensile testing equipment used to conduct the breaking load tests was at Mennen Dongen BV in The Netherlands. This equipment (Figure 9.1) may be used for testing at loads up to 14,000 kN (14 MN or 1,400 tonnes). Mennens is a ISO 9001 certified company, and the test machine is calibrated to Class 1 according to ISO 7500. Appendix B presents a calibration certificate for this equipment.

High speed camera filming of the breaking load test on the samples was undertaken to examine whether there was any difference in the failure mode of the three samples. Figure 9.1 shows the camera being set up, and Figure 9.2 the camera and all the lighting ready for the test.

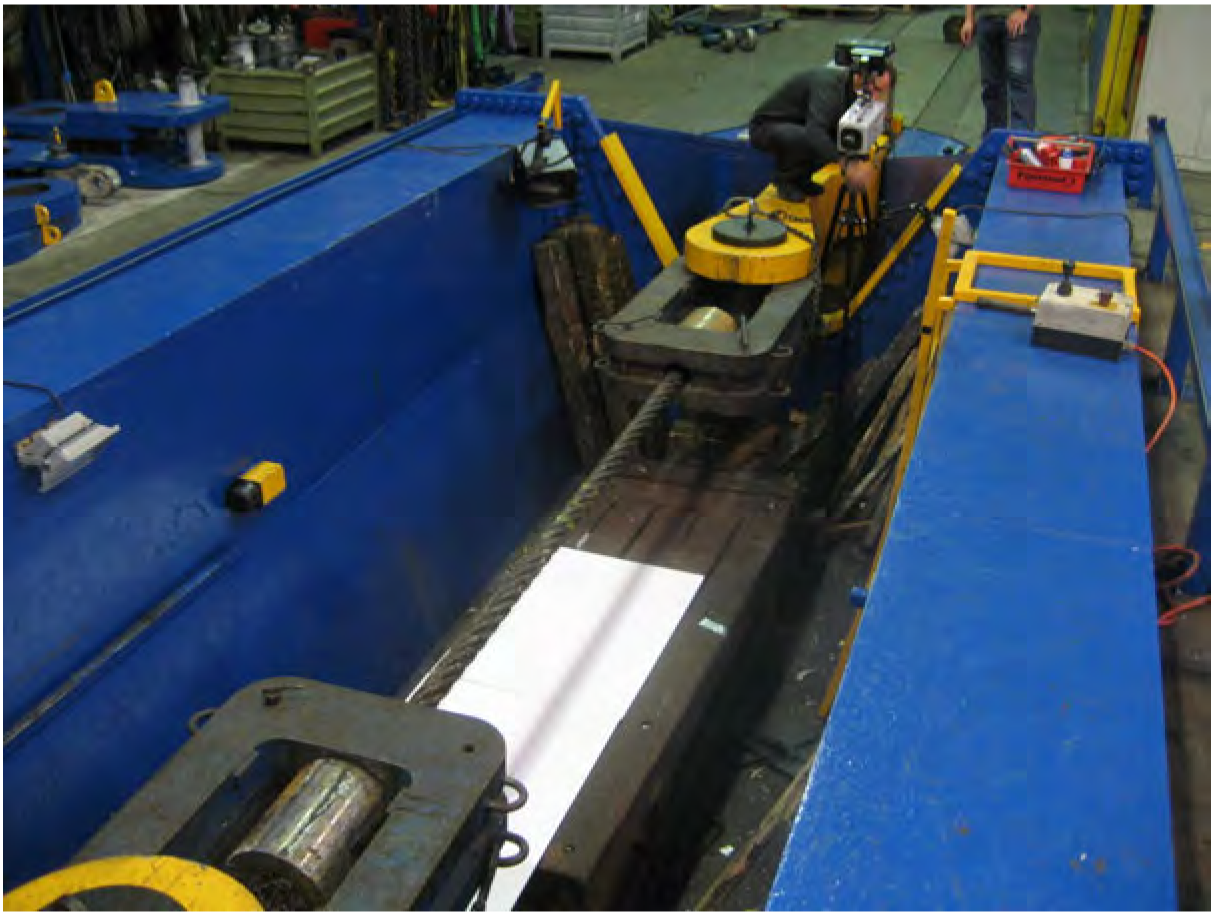


Figure 9.1: Wire rope sample ready for testing in Mennens' 1,400 tonne tensile testing machine.

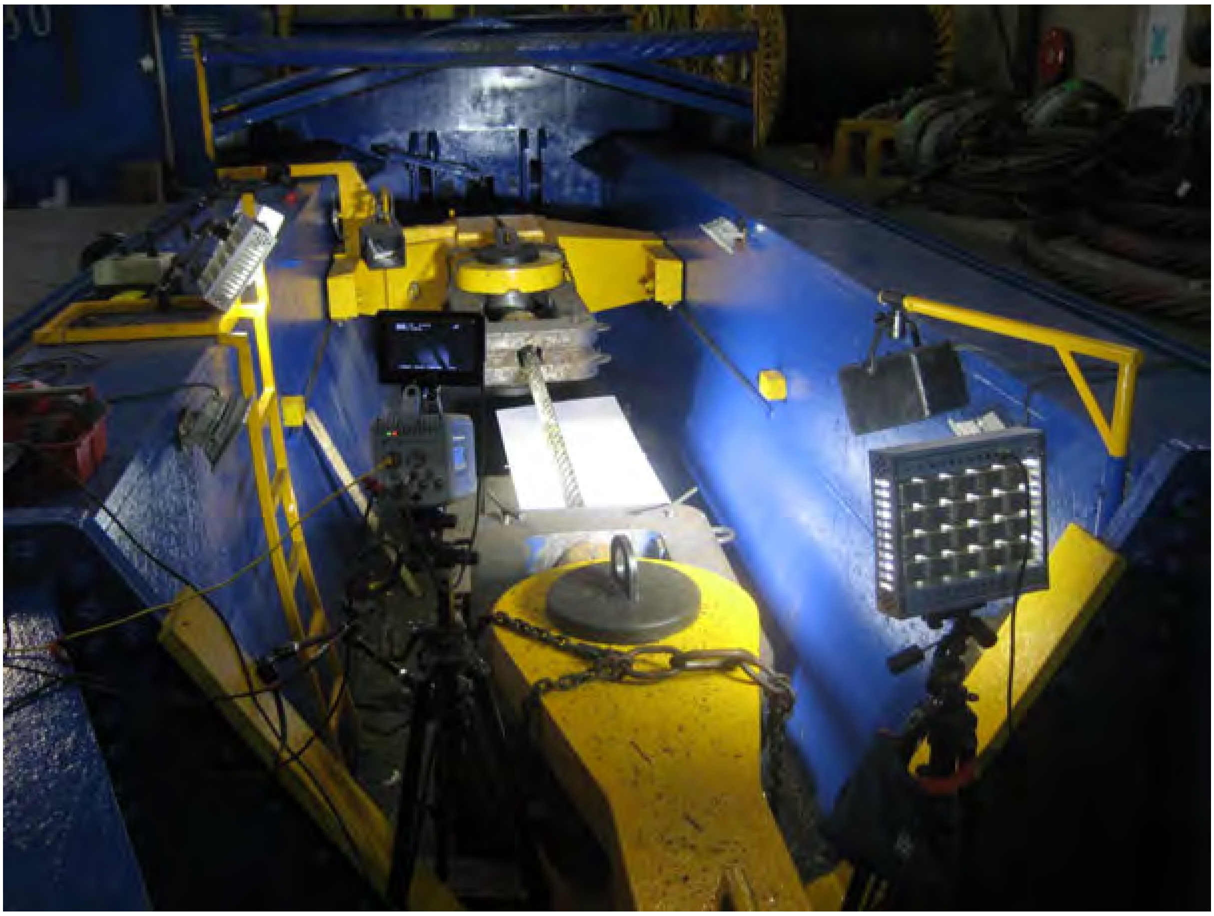


Figure 9.2: Wire rope sample ready for testing with high speed filming equipment in place.

9.2 Results of the breaking load tests

Table 9.1 presents the results of the breaking strength measurements conducted on the three samples. Appendix C presents the Mennens tests reports for these tests.

Sample	Breaking load [kN]	Breaking load [%F_{min}]	Breaking load [%ABL]
Drum	4,493	94.4	92.7
Tug side	3,815	80.2	78.7
Bridle	3,707	77.9	76.5

Table 9.1: Results of the breaking strength measurement on the three wire rope samples.

Figures 9.3 - 9.5 show the drum sample following testing. It may be seen that the sample failed clear of the terminations (Figures 9.3 and 9.4). Examination of the failure showed that the majority of the wire failures were from tensile overload (as would be expected), with a few shear type failures (given the helical nature of wire rope, this is also as expected).

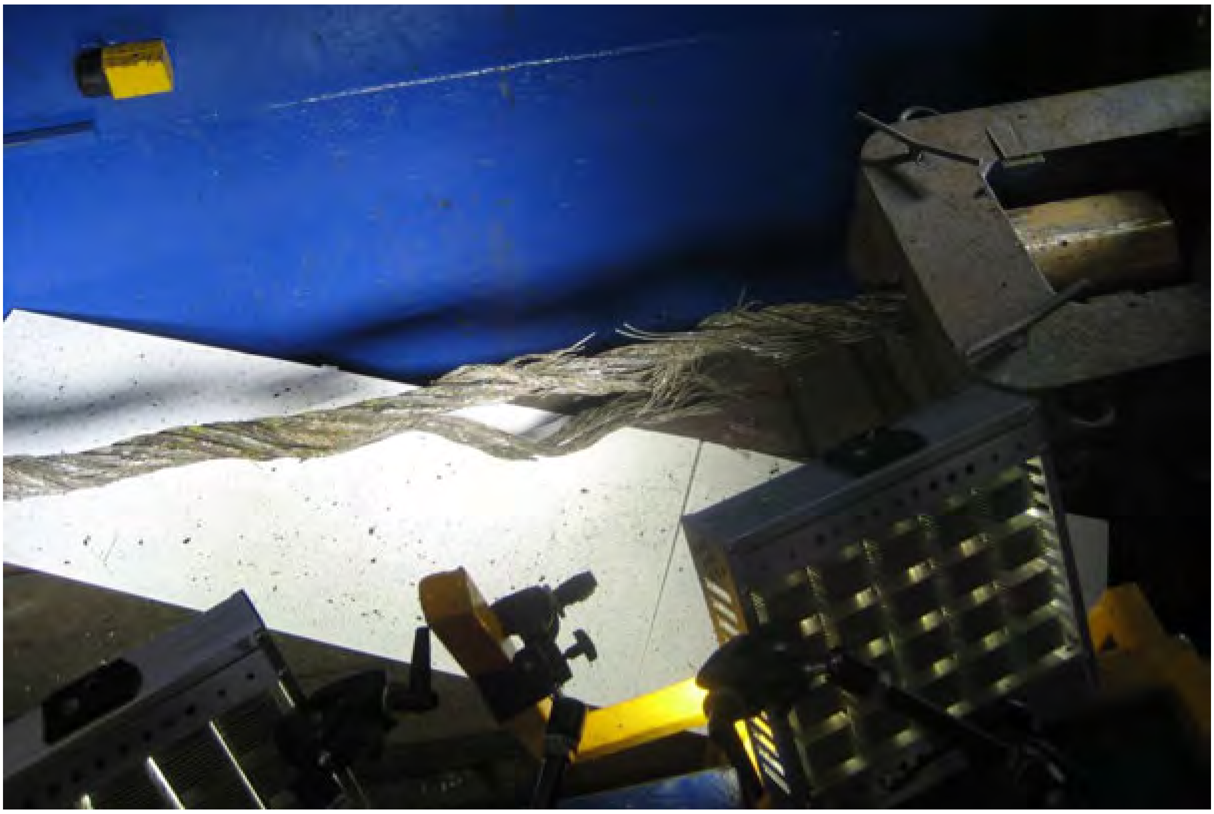


Figure 9.3: Drum sample in test machine after testing.

Figure 9.4: Drum sample failure clear of termination.

Figure 9.5: Drum sample detailed view on failure region.

Figure 9.6 shows the broken wires which fell out of the tug side sample when it was terminated for testing. The wires are largely from the IWRC, which as the initial inspection had shown was in fairly poor condition. In addition to the IWRC wires there were also some outer strand outer layer wire breaks. The tug side sample failed mid-length (Figure 9.7).

Figure 9.6: Tug side sample - broken wires found in preparation of sample terminations. (Mostly IWRC wires, but also some outer strand outer wires).

Figure 9.7: Tug side sample after testing, failure mid-length.

Figures 9.8 and 9.9 show views on the groups of wire failures after testing of the tug side sample. The inner layers of the main strands may b readily identified by their paler colour. It can be seen that these wires failed with tensile cup and cone type failures. There were also some shear failures (e.g. centre of Figure 9.9).

Figure 9.8: Tug side sample after testing, detailed view on wire failures.

Figure 9.9: Tug side sample after testing, detailed view on wire failures.

As with the tug side sample, the core of the IWRC was found to be mostly in pieces when the sample was prepared for testing (Figure 9.10). Additionally, there were also breaks in some outer strand outer wires. As with the other samples, the bridle sample failed clear of the terminations (Figure 9.11).
Figure 9.12 shows a group of shear wire breaks on one of the outer strands after testing. This view is interesting as it shows clearly that there were three existing wire breaks in the sample (corroded fracture surfaces), and two wires which were broken in the breaking load test (fresh ends).

Figure 9.10: Broken wires found in preparation of Bridle sample terminations - mostly IWRC wires.

Figure 9.11: Bridle sample after testing, failure mid-length.

Figure 9.12: Bridle sample after testing, detailed view on wire failures (old - rusty ends, new - shiny).

10 Strip down inspection of 1 m samples

Sections 1 m long were selected for visual inspection and mechanical testing of representative wires from across the wire rope construction. As noted above, the rig side sample had suffered too much post failure damage to permit a fair assessment of the condition of the wire rope at the time of the incident, thus the following samples were inspected:

- Drum sample;
- Tug side sample; and,
- Bridle sample.

The visual inspection of the samples was in line with the criteria set out in BS ISO 4309:2010 [**5**], and paid particular attention to corrosion, lubrication and mechanical damage.

Tests were performed on wires taken from positions throughout the wire rope cross section to assess:

- Tensile strength;
- Torsions to failure;
- Reverse bends to failure; and,
- Residual zinc coat weight.

10.1 Strip down inspection of Drum Sample

Figure 10.1 shows the general condition of the drum sample. The crown position of the sample was lacking in lubricant, and there were areas of white zinc oxide associated with loss of galvanic protection. In some areas light corrosion was noted (Figure 10.2). There were also patches of what appeared to be mud. It is not known when this was deposited on the wire rope surface.

In the valley positions between strands the lubricant level was very good, but it was hard and glassy in appearance. It is noted that the wire rope inspection certificate states that the lubricant is 'D / bitumin lube', so it is likely that this lubricant is the original as manufactured.

Figure 10.3 shows the sample with two outer strands removed to reveal the IWRC. It may be seen that the lubricant level on the IWRC is very low, and what lubricant there is, is dry.

Figure 10.1: General condition of the drum sample.

Figure 10.2: Detailed view on the drum sample showing an area of corrosion. Note also the 'mud deposits' and the good level of lubricant in the valleys.

Figure 10.3: Drum sample with two outer strands removed to show the condition of the IWRC - the lubricant level is very low. Note also the light corrosion on the outer strand (top right) and the glassy bitumous lubricant in the valley positions (of the outer strands).

Figure 10.4 shows an outer strand after removal from the wire rope sample and partially cleaned. Sections of lubricant have been left in place to highlight the difference in residual galvanising levels between the section of strand normally on the outside of the wire rope, and that facing towards the IWRC.

Figure 10.4: Drum sample outer strand partially cleaned to show the difference in residual galvanising levels for sections on the inside and outside of the wire rope.

The outer strand was then stripped down layer by layer to permit assessment of the internal condition. Figures 10.5 - 10.7 show the second and third layers and core wire of the outer strand. It may be seen that the inner layers and core of the outer strand are well lubricated and have retained a good galvanising covering. No signs of degradation or wear were noted.

before cleaning

after cleaning

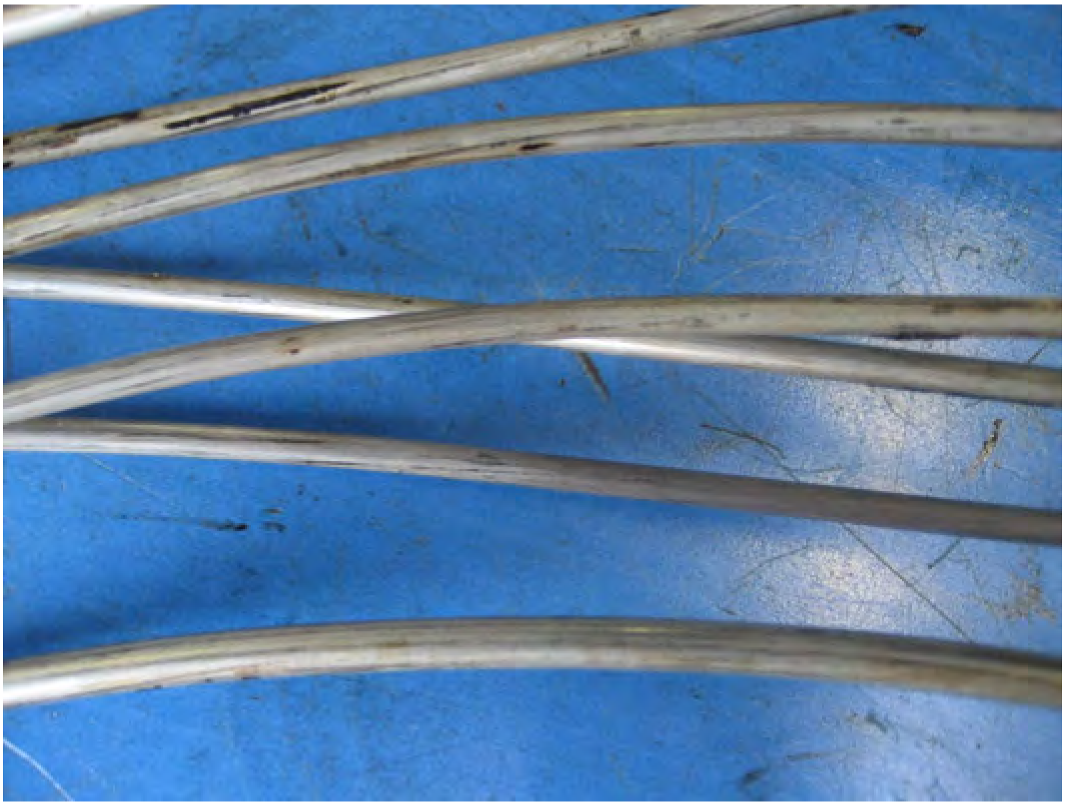
Figure 10.5: Drum sample outer strand - second layer of wires.

before cleaning

after cleaning

Figure 10.6: Drum sample outer strand - third layer of wires.

before cleaning



after cleaning

Figure 10.7: Drum sample outer strand - third layer of wires and core wire (bottom).

Figure 10.8 shows the Manufacturers' marker tape which was found along the outside of the IWRC. It confirms that the wire rope was manufactured by Usha Martin.

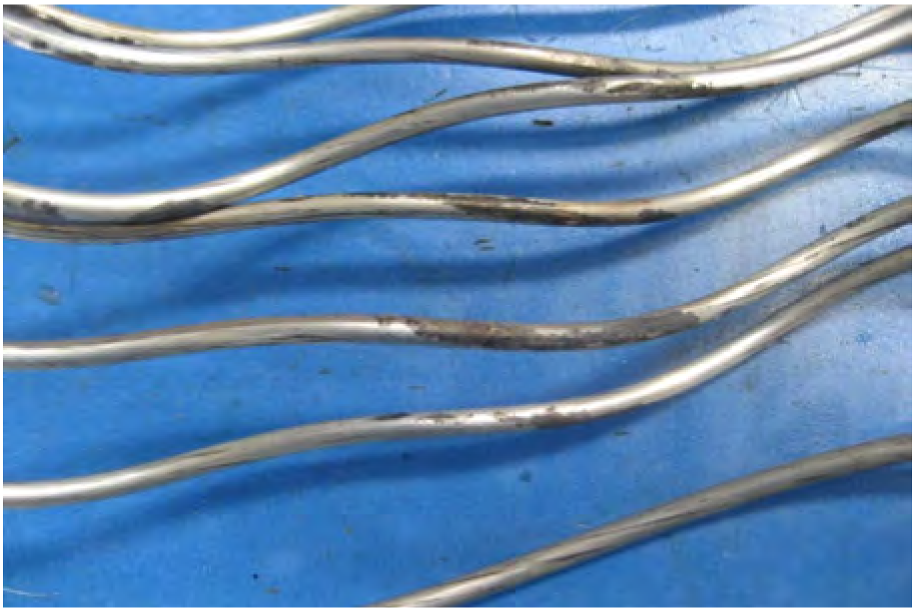
Figure 10.8: Manufacturers' identification tape found under the outer strands and on the IWRC (Drum sample).

Figure 10.9 shows the drum sample with all the outer strands removed to show the IWRC. As noted above, the lubricant level is low and what is there appears denatured and powdery. An outer strand was removed to permit further examination. Figure 10.10 shows the core strand after cleaning. It may be seen that the residual galvanising is patchy, but there is no corrosion as such on the core strand. Dismantling the core strand shows that the lubricant inside the strands is good and sticky, and that the residual zinc is a little patchy, but overall good (Figure 10.11).

Figure 10.9: Drum sample IWRC.

Figure 10.10: Drum sample IWRC outer strand cleaned.

before cleaning



after cleaning

Figure 10.11: Drum sample IWRC outer strand outer wires and core (bottom).

Figure 10.12 shows the IWRC core strand, which is similar in appearance to the IWRC, but with more lubricant. On cleaning the outer surface of the core (Figure 10.13) it may be seen that the residual galvanising is also patchy, but as with the outer strands, there is no corrosion. Figure 10.14 shows the core after dismantling. It may be seen that the lubricant level is good, and appears sticky in nature. The galvanising is a little patchy on the more exposed surfaces.

Figure 10.12: Drum sample IWRC core strand.

Figure 10.13: Drum sample IWRC core strand cleaned.

before cleaning

after cleaning

Figure 10.14: Drum sample IWRC outer wires and core strand (bottom) cleaned.

Following inspection of the drum sample all six outer strands and the IWRC were stripped down to check for wire breaks. None were found.

Wires were selected from various positions in the wire rope construction for the measurement of the level of residual galvanising as well as tension, torsion and reverse bending tests. The results of these tests will be presented later in this report.

10.2 Strip down inspection of the tug side sample

Figure 10.15 shows the general condition of the tug side sample in the 'as received' condition. Its appearance is quite different to that of the drum sample (cf. Figure 10.1). The lubricant level was low to none, and there was a covering of light corrosion along the length. A single wire break was noted in one of the outer strands in the valley position, that is at the position where the outer strands contact one another. Figure 10.16 shows a detailed view on the wire break which had a 45° shear failures fracture surface typical of combined axial and transverse loading (axial load in the wire rope combined with transverse load as two strands press together). Note also that there is very little if any residual galvanising and the corrosion which has just started to roughen the surface of the wires.

Figure 10.15: General condition of the tug side sample before cleaning.

Figure 10.16: Detailed view on single wire break noted in valley position on tug side sample.

Figure 10.17 shows the tug side sample with two outer strands removed to reveal the IWRC. The lubricant level was generally low (a single large patch was noted in one area (Figure 10.18)). As with the outer strands the residual galvanising was low, and there was corrosion along the length of the core. Many wire breaks were noted in the IWRC outer strands (Figures 10.17 - 10.20). The remaining outer strands were carefully removed to permit full inspection of the core (Figure 10.18).

Figure 10.17: Tug side sample with two outer strands removed to reveal IWRC.

Figure 10.18: Tug side sample, general condition of IWRC. Five wires dropped out of the construction as the outer strands were removed. Some areas of good level, good nature lubricant, but on the whole the lubricant level was low and dry.

The majority of the wire breaks found in the core strands were already existing at the time of the incident (rusted features) see Figure 10.19 (it is not possible to say how old they were), but some were recent and probably as a result of the severe weather which the wire rope experienced during the tow at the time of the incident (Figure 10.20).

Figure 10.19: Wire breaks found in tug side sample IWRC outer strands (existing wire break arrowed).

Figure 10.20: Wire breaks found in tug side sample IWRC outer strands (recent wire break arrowed).

Figure 10.21 shows the IWRC with two strands removed to show the core. The lubricant level was much better than on the outer strands, but it was dry and flaky (Figure 10.22). There did not appear to be much corrosion - the main feature noted was that the whole core strand was broken through in several places. Once the outer strands were all removed it could be seen that the core strand was broken through completely in five places (Figure 10.23), as well as having other wire breaks along its length.

Figure 10.21: Tug side sample, IWRC with two strands removed to show core. Core strand broken through. Good level of lubricant.

Figure 10.22: Tug side sample, dry lubricant which dropped out of the wire rope.

Figure 10.23: Tug side sample IWRC core - broken through in five places (6 pieces) over 1 m length.

Figures 10.24 and 10.25 show sections of the IWRC core and an outer strand after cleaning. The IWRC core has some residual galvanising present, whilst the core strand has very little if any. The corroded appearance noted above (Figure 10.21) has cleaned off. The wire failures in both the strand and the core are the shear type, which are to be expected as the IWRC experiences high transverse loads as it supports the main outer strands in the wire rope.

Figure 10.24: Tug side sample IWRC core strand after cleaning.

Figure 10.25: Tug side sample IWRC outer strand after cleaning.

Figure 10.26 shows one of the main outer strands after cleaning. The wire break was located in the valley position in the wire rope and was not detected until the strands were removed to inspect the core. (In all four outer strand outer wire breaks were found in the 1 m sample - only one of which was found before the wire rope was dismantled.) The break has initiated at the wear patch on the surface of the wire, and failed in a mixture of shear and fatigue. The 'beach' marks characteristic of fatigue may be seen on the right hand edge of the fracture surface. It is also noted that there is very little residual galvanising left on the surface of the strand.

Figure 10.26: Tug side sample main outer strand after cleaning.

Figure 10.27 shows an outer strand with four outer wires removed to reveal the second layer. The contrast between the outer layer and second layer is quite marked: the level of lubricant in the second layer is better, and although still low, the residual galvanising seems better. Figure 10.28 shows the third layer of wires in the main strand before and after cleaning. This 'far' into the strand the lubricant is much better both in level and nature and the residual galvanising is also higher. Similarly the strand core wire had very good lubricant and high residual galvanising levels. No corrosion was noted in any of the inner layers of the outer strand inspected.

Following inspection of the sample, all outer strands were completely dismantled to check for wire breaks. Apart from the four outer strand outer wire breaks, no internal wire breaks were found. Indeed, the inside of the main strands were in generally good condition.

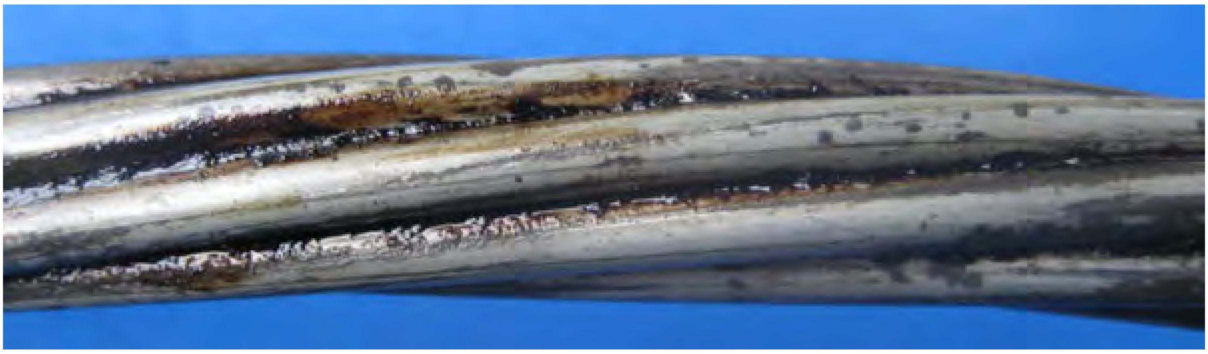
In contrast, as noted above, the IWRC was in very poor condition. The strands and core were stripped down to count the wire breaks. In all there were 62 breaks in the outer strands and 59 in the IWRC core (total 121 wire breaks). Obviously there will be a loss of strength associated with this level of degradation: the IWRC of a six strand wire rope typically carries about 15% of the wire rope strength. What is more important is that a core with this level of damage will not perform its main function which is to support the outer strands so that as it bends they are free to slide and do not contact one another.

before cleaning

after cleaning

Figure 10.27: Tug side sample, main outer strand with four outer layer wires removed to expose the second layer.

before cleaning



after cleaning

Figure 10.28: Tug side sample, main outer strand third layer of wires.

before cleaning

after cleaning

Figure 10.29: Tug side sample, main outer strand core wire.

10.3 Strip down inspection of the bridle sample

Figure 10.30 shows a general view of the bridle sample. It is fairly similar in appearance to the tug side sample: the external lubricant has gone and the surface of the wire rope is covered with a light corrosion which has just started to cause a roughening of the wire surface (Figure 10.31). Seven outer strand outer wire breaks were counted along the length (four of which may be seen in Figure 10.30). All wire breaks were in the valley positions and shear type in appearance.

Figure 10.30: General view on bridle sample.

Figure 10.31: Detailed view on bridle sample - note no visible galvanising and a uniform covering of corrosion causing roughening of the surface of the wires.

Figures 10.32 and 10.33 show the bridle sample with two outer strands removed to expose the IWRC. It may be seen that in some areas the lubricant was a quite a high level, if somewhat denatured (Figure 10.32), whilst in other places along the core the level was low (Figure 10.33).

Figure 10.32: Bridle sample with two outer strands removed - area of good lubrication on IWRC.

Figure 10.33: Bridle sample with two outer strands removed - area of low lubrication on IWRC.

The outer strands were all removed to permit a detailed inspection of the core (Figure 10.34). In general the lubricant level was higher than the tug side sample, making it harder to assess for wire breaks (the sample was subsequently dismantled to allow a full count to be made). It was also noted that there was sand on the surface of the IWRC. It is not clear how this came to be on the wire rope, particularly in this position in the wire rope construction, but with the lubricant missing from between the outer layer of strands it would be possible for the sane to enter and become trapped in the wire rope.

Figure 10.34: Bridle sample IWRC. Note the lubricant level is reasonable if a little dry and denatured, also the grains of sand.

Figure 10.35 shows the IWRC with three outer strands removed. The condition is very similar to the tug side sample. The lubricant is at a reasonable level, if a little dry. As with the tug side sample the core strand was broken through in several (in this case four) places (Figure 10.36).

The wire failures in the core strand were typically shear type with the characteristic 45° fracture surface (Figure 10.37). Figure 10.38 shows a dismantled section of core strand before and after cleaning. It can be seen that the residual galvanising level on the wires is very low, with only a few small patches observed, however the wires do not appear to be corroded.

Figure 10.39 shows a IWRC strand after removal from the core and cleaning. The wire breaks are typical of those found in the core strands. As with the tug side sample, all strands and the core were stripped down to count the number of breaks. In the IWRC outer strands 69 wire breaks were counted and in the core 48 (total 117 breaks in 1 m of IWRC).

Figure 10.40 shows a section of dismantled IWRC strand before and after cleaning. As with the core strand the residual galvanising is very low. Additionally, some areas of the wire surface show a roughening from the start of corrosion.

Figure 10.35: Bridle sample IWRC with three outer strands removed to show the core (all core strand wires broken).

Figure 10.36: Bridle sample IWRC with three outer strands removed to show the core (all core strand wires broken).

Figure 10.37: Bridle sample IWRC core showing typical shear type wire failures.

before cleaning

after cleaning

Figure 10.38: Bridle sample IWRC core, (some) outer wires and core wire (bottom).

Figure 10.39: Bridle sample IWRC outer strand (after cleaning).

before cleaning

after cleaning

Figure 10.40: Bridle sample IWRC strand, (some) outer wires and core wire (bottom).

Turning to consider the main load bearing outer strands, Figure 10.41 shows a strand as removed from the sample. The darker (upper) section would have been towards the inside (IWRC) of the wire rope. The lubricant level is a little better than the lower (outer) section. The interface between these two areas is at the valley position in the wire rope. Note the wire break in the outer wire.

Figure 10.42 shows this section of strand after cleaning. A series of inter-strand elliptical wear patches may be seen. In time more fatigue cracks and wire failures would have initiated at these positions. Note also that the surface of the wires on the outside of the wire rope has become roughened and more pitted from corrosion.

Figure 10.41: Bridle sample main strand as removed from the sample. The upper (darker coloured section) would have been towards the inside (IWRC), whilst the lighter section was on the outside of the wire rope. The intersection of these two areas is the valley position between the strands. Note the wire break at this interface (arrowed).

Figure 10.42: Bridle sample main strand after cleaning. Note the series of elliptical wear patches along the valley position from which wire breaks have/will initiate.

Figure 10.43 shows the second layer of the main strand before and after cleaning. The level of lubricant is already much better than on the outer layer of wires, although somewhat flaky and denatured. The cleaned wires show very little residual galvanising, and a slight roughening of the surface indicates the onset of corrosion.

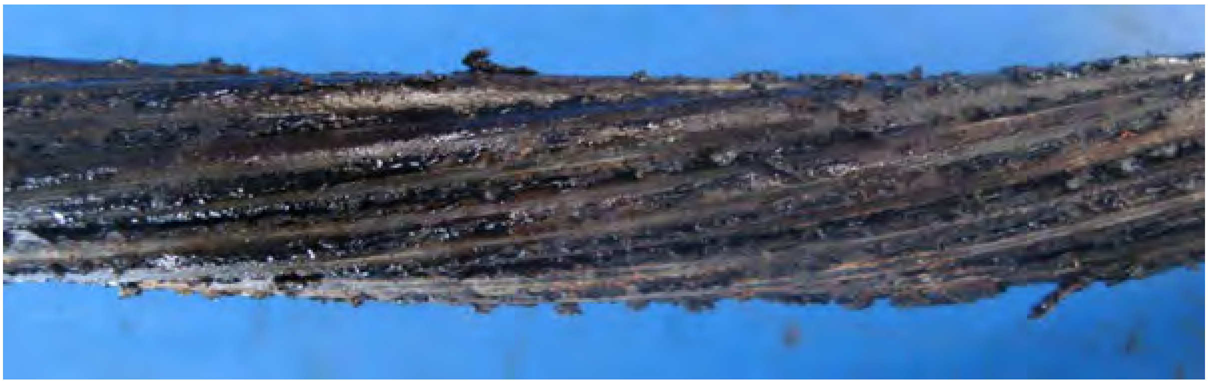
As with the tug side sample, further 'into' the strand the nature of the lubricant and level was better, and the wires had retained more of their galvanic protection (Figures 10.44 and 10.45). No corrosion was noted in the third and core layers.

As with the IWRC, the outer strands were completely dismantled to check for broken wires. A total of nine outer wire breaks were found. There were no wire breaks in the second, third or core layers.

before cleaning

after cleaning

Figure 10.43: Bridle sample main strand second layer of wires.



before cleaning

after cleaning

Figure 10.44: Bridle sample main strand third layer of wires.

before cleaning

after cleaning

Figure 10.45: Bridle sample main strand (some of) the third layer of wires and core wire (bottom).

10.4 Measurements made on strip down samples

In addition to the visual inspection and the mechanical tests on the wires (which will be reported in the next sections, basic dimensions diameter and lay length of the wire rope samples were checked (Table 10.1). It can be seen that the average diameters were quite similar to the as manufactured value, as were the lay lengths. The bridle sample had the greatest diameter reduction at 2.27%, but this is still within an acceptable value for this type of construction [**5**, Table 5]. For completeness, Table 10.2 summarises the wire breaks found.

Sample	Lay length [mm]	Average diameter [mm]	% Loss average diameter [mm]
As manufactured	534	78.46	-
Drum	540	78.55	- 0.11
Tug side	575	77.79	0.85
Bridle	540	76.68	2.27

Table 10.1: Summary of measured lay-lengths and wire rope diameters on inspected sections.

Sample	IWRC core	IWRC strands	Outer strand outer wires
Drum	0	0	0
Tug side	59	62	4
Bridle	48	69	9

Table 10.2: Summary of broken wires found on inspected sections.

11 Inspection of tug side failure

Inspection of the main tow line failure focussed on the tug side failure, as the rig side failure had suffered considerable abrasion damage post break.

The initial inspection (§5.2) had highlighted the condition of the IWRC, and the multiple wire breaks on the outer strand wires leading up to the position of the main failure.

Figures 11.1 and 11.2 show the main failure of two of the strands. It may be seen that the failure position is generally at the same axial location, but with some longer wires which were probably already broken and pulled away from the construction (e.g. Figure 11.3). As with the break load samples (§9 tug side and bridle), the tendency was for the main strand inner wires to break with cup and cone type fractures (Figure 11.4), and the outer strand outer wires to break with predominantly shear failures (Figure 11.2, Figure 11.5).

The coloured tapes mark wires which were subsequently removed and sent for SEM examination (Figures 11.3 - 11.5).

The nature and distribution of the wire breaks on the main failure point towards failure primarily from tensile overload on a sample weakened by wire failures caused before or during the storm.

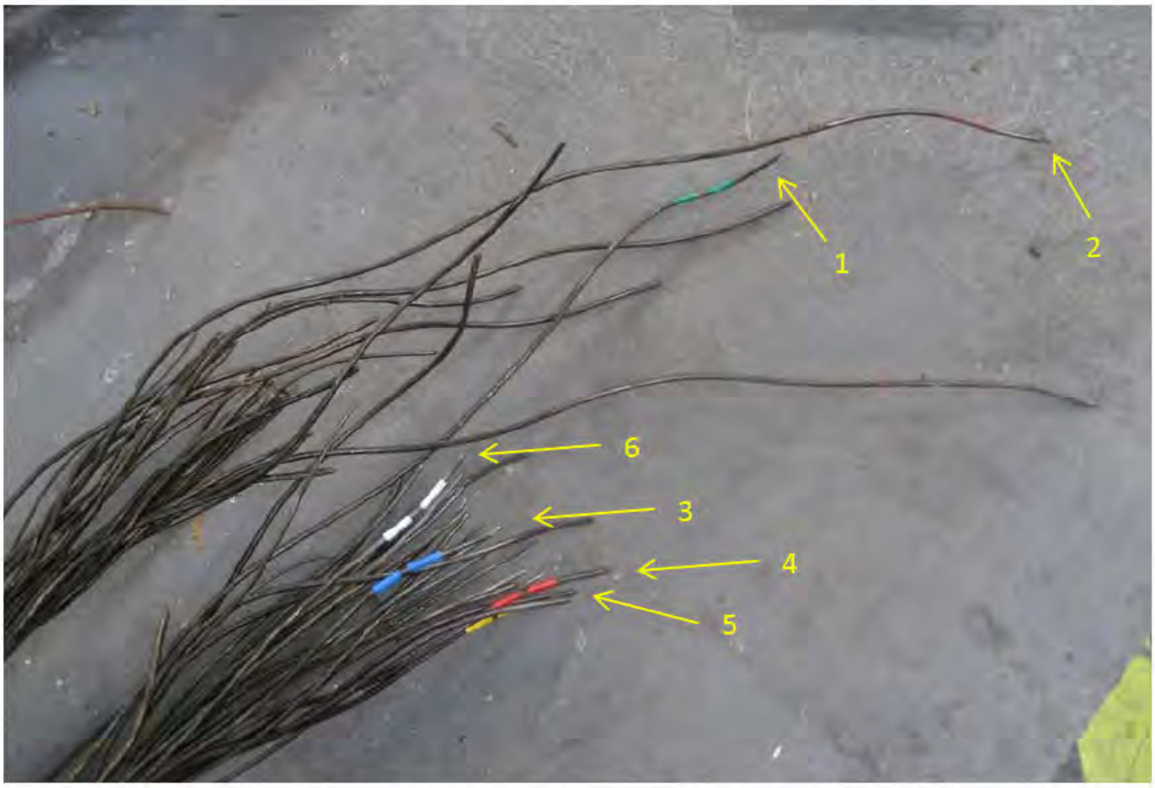


Figure 11.1: Tug side sample main failure Locations and ID numbers of wire fracture surfaces taken for further examination.

Figure 11.2: Tug side sample main failure, detailed view on one strand.

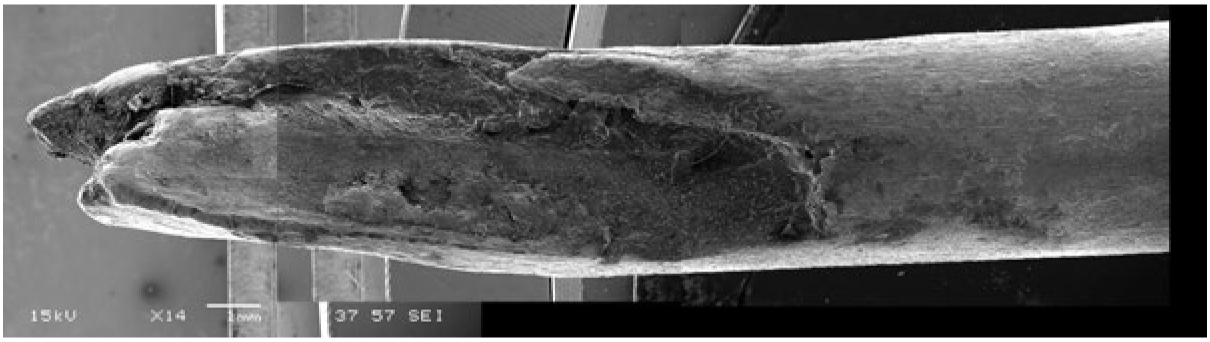


Figure 11.3: Composite SEM image of Wire 2 showing non tensile type failure.

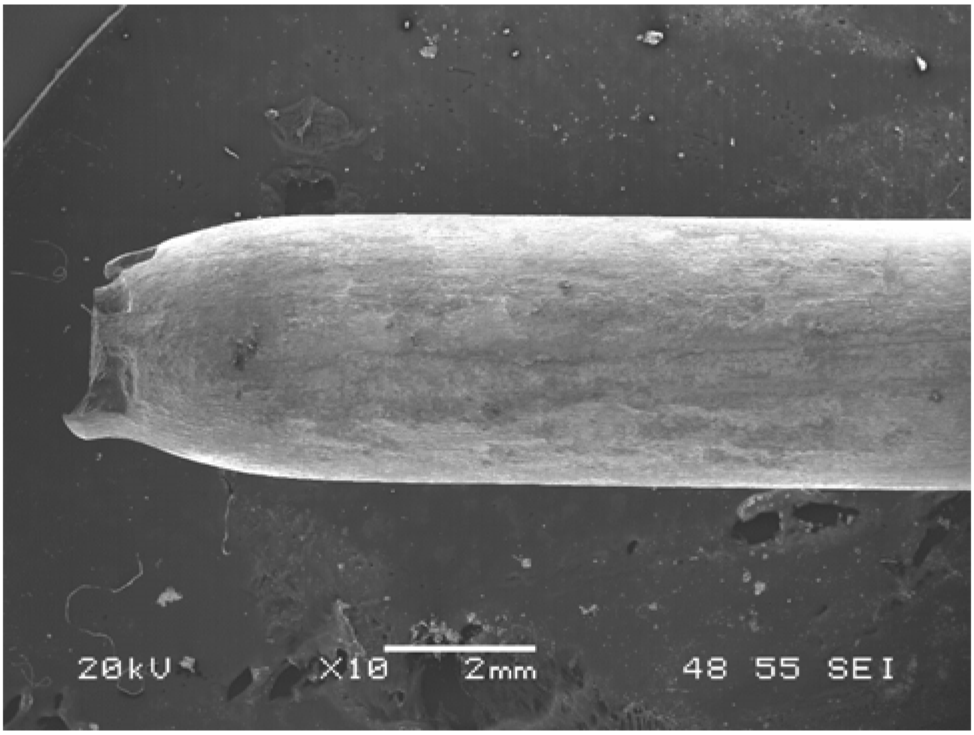


Figure 11.4: SEM image of tensile (cup and cone) failure of Wire 6 (outer strand second layer large wire).

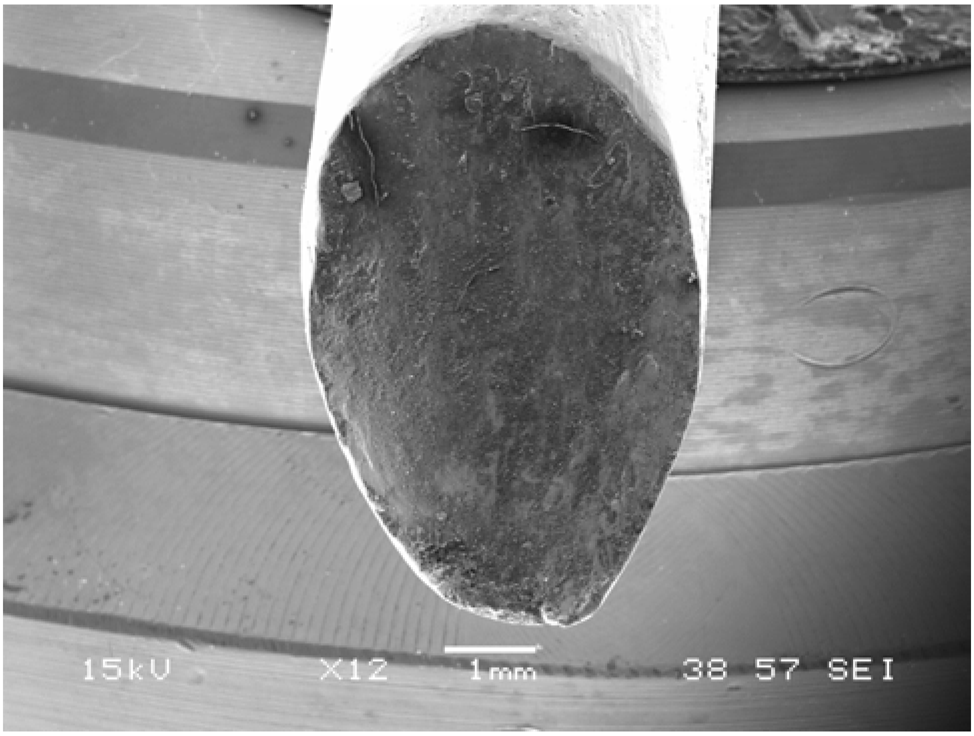


Figure 11.5: SEM image of shear failure of Wire 4 (outer strand outer wire).

12 Mechanical tests on individual wires

Mechanical tests on the component wires of a wire rope are a useful means of assessing the rope wire's general condition. The results of such tests may be compared with the data from the wire rope manufacturer (where available) and also with the relevant standard which specifies minimum requirements.

It is immediately noted that the minimum standard requirements and manufacturers' data are for tests which are undertaken on the wire stock before it is spun into a wire rope. In the work reported here, wires have been removed from the ex-service wire rope and cleaned and straightened with care in order to allow testing. For the wire rope which is the subject of this study, the main outer layer of the outer strands in the construction were subject to die-forming (see Figure 2.1), which has led to non-circular wire cross sections. Previous testing has shown that this can have quite a large effect on the results of the tensile strength tests, and to a lesser extent an effect on the torsion test results, and the bending test results. It is noted that the die-forming of the wire rope under discussion here is not as heavy as in others, but it should be taken into account when interpreting the results of the tests. The core wires (in the strands) and wires in the wire strand core should be relatively unaffected by the die-forming and might be expected to give more consistent results.

Turning to the relevant standard, for the tests undertaken here, where possible, the results will be compared with API 9A [**1**]. It is noted that the API standard does not specify requirements for the reverse bend test, and so the results of these tests will be compared with the criteria set out in BS EN 10264-2:2012 [**6**] which was effective at the time of the wire rope manufacture.

The following types of mechanical tests were undertaken on wires from the wire rope strands:

- Tensile tests;
- Torsion tests; and,
- Reverse bend tests

Attention was focussed on the outer strands and the outer wires of the outer strands, since these represent the greatest percentage of load bearing area in the wire rope. Thus, for the construction under consideration here it was decided to take:

- Three outer wires from each of four outer strands;
- One of each wire size from the second and third layers of three outer strands;
- One core wire from one outer strand;
- One wire of each size from the IWRC strand; and,
- One of wire of each size from the IWRC core.

Table 12.1 summarises the test samples which were extracted from the wire rope (one set of each for the tension, torsion and bending tests).

Strand	**Wire position**	**Number of tests**
Outer strand 1*	outer wire	3
	2nd layer large and small	1 + 1
	Third layer	1
	Core	1
Outer strand 2*	outer wire	3
	2nd layer large and small	1 + 1
	Third layer	1
Outer strand 3*	outer wire	3
	2nd layer large and small	1 + 1
	Third layer	1
Outer strand 4*	outer wire	3
IWRC strand	outer layer	1
	core	1
IWRC core	outer layer	1
	core	1
TOTAL		**26**
*Note the strand numbers are completely arbitrary, strands were selected at random		

Table 12.1: Summary of the samples taken from the wire rope for tensile, torsion and bend testing.

12.1 Tensile tests

Tensile tests were undertaken on individual wires removed from the strands disassembled under §12. Especial care was taken when selecting samples from the very outer layers of the wire rope to avoid those which might have been subject to undue mechanical damage (e.g. abrasion).

Testing was conducted in accordance with ISO 10425:2003 [**7**] Annex B.

The wires were removed from the wire rope construction, labelled and cleaned. Following cleaning they were straightened as much as practical by bending in the soft jaws of a vice or through a specially designed jig. It is noted that whilst the wires were straightened as much as possible, they were not perfectly straight. Hence it was not possible to measure their elongation to failure as the initial part of the load-stroke relationship was affected by the final wire straightening under load.

Once straightened, the wires were cut to the correct length for testing (nominal 450 mm). The wires were tested in TTI Testing's universal servo-hydraulic testing machine, with special grips for wires, (Figure 12.1). The tests were conducted in stroke control with a test speed of 0.3 mm/s. (Appendix D presents the calibration certificate for this machine.)

Figure 12.1: Tensile testing of wire in 250 kN tensile testing machine.

12.2 Torsion tests

Torsion tests were undertaken on a set of wires as detailed in Table 12.1. The tests were conducted in accordance with ISO 7800:2012 [**8**]. As is permitted by the standard, a gauge length of 300 mm was used for all tests, the results being scaled to provide a number of turns to failure for a length of $100d_w$ (where d_w is the wire diameter).

12.3 Reverse bend test

Reverse bend tests were undertaken on a set of wires as detailed in Table 12.1. The tests were conducted in accordance with ISO 7801:1984 [**9**].

13 Wire zinc coat weight

The thickness (weight) of the protective galvanising coat on the wires was determined in accordance with the gravimetric method described in BS EN 10244-1:2001 [**10**]. This method produces an average zinc coat weight for the sample.

Since the length of the samples to be tested was relatively short (ca. 100 mm), care was taken to select samples which were not only representative of the wires in the wire rope, but of their position within the wire rope. This is particularly so for the outer strand outer wires, which are in turn 'inside' the wire rope and in the crown position over half a strand lay-length (see Figure 13.1). In order to avoid this uncertainty, all the outer wires of an outer strand sample were tested. Additionally, two wires of each size from the outer strand second layer were tested, along with single wires of each other size/position remaining from a strand and from the IWRC. Locations of the wires selected for zinc weight examination are detailed in Table 13.1.

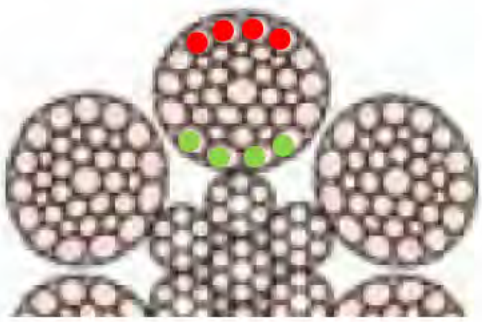


Figure 13.1: Schematic diagram showing how the outer strand outer wires move from the relatively protected position 'inside the wire rope (green spots) to 'outside' (red spots) over half a strand lay-length.

Strand	Wire position	Number of tests
Outer strand	outer wire	14
	2nd layer large and small	2 + 2
	Third layer	1
	Core	1
IWRC strand	outer layer	1
	core	1
IWRC core	outer layer	1
	core	1
TOTAL		**24**

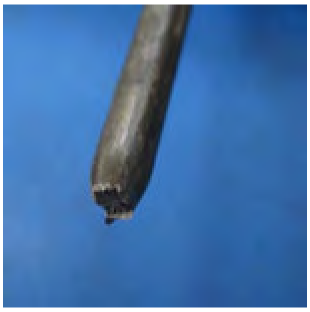
Table 13.1: Summary of the samples taken for zinc weight measurement.

14 Results of the mechanical tests

Full results of the mechanical testing (tensile, torsion and reverse bend) are presented in a series of Tables in Appendix E.

Considering first the results of the tests undertaken on the drum sample wires:

- The results of the tensile tests were very consistent, and very good. With the exception of one wire (at 99%) all wires were in the range of 101% - 109% of the average wire grade stated on the manufacturer's certificate (see Table 2.2 and Appendix A). Wire breaks were typical cup and cone type failures, which was as expected (Figure 14.1).



OS1 OW1

OS1 3L

OS1 CW

IWRC CS CW

Figure 14.1: Typical appearance of wire failures in tensile tests on wires from the drum sample.

- The results of the torsion tests were a little more varied. The wires either passed by some margin or failed rapidly (Figure 14.2). The torsion test is very sensitive to surface condition, and it maybe that surface of the outer wires on some of the outer strands was damaged leading to premature failure. The results of the tests on the wires from the inside of the main strands were generally very consistent and good. The tests undertaken on the IWRC wires were generally low. It is thought that the reason for this may be the effort put into straightening the wires for testing. It is easy to damage a wire despite taking great care in sample preparation. In contrast the core wire which required no straightening performed well.

Figure 14.2: Appearance of wire failures in torsion tests on wires from the drum sample. (Top OS OW1 (7 turns/100d_w), bottom OS CW (27 turns/100d_w)).

- The reverse bend test (in addition to the torsion test) is means of assessing a wire's ductility. The API 9A [**1**] does not have a minimum requirement for wires tested in this manner, so the requirements of Standard 10264-2 [**6**] have been used. All the wires in the reverse bend tests satisfied the minimum requirements of the Standard. This would suggest that the wire material was ductile, but in the torsion tests the surface had been damaged.

Turning to the tug side sample:

- The results of the tensile tests on the outer strand outer wires were consistently all a bit low (one at 83%, others at 92% to 99%), (Figure 14.3). The results of the tests on the main strand inner wires were all very good (100% to 109%). The IWRC wires were in the range 97% to 104% of the assumed original grade.

OS1 OW2

OS1 CW

Figure 14.3: Typical appearance of wire failures in tensile tests on wires from the tug side sample.

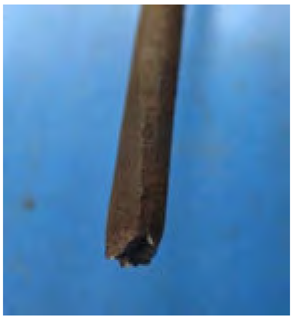
- The results of the torsion tests on the outer strand outer wires were all very low, typically about 10% - 30% of the standard minimum requirement. The results of these tests were significantly affected by the surface damage (wear) and corrosion noted on the sample during the inspection (Figure 14.4). In contrast, all the wires on the inside of the main strands performed well. These wires had not experienced surface damage and were not corroded. The IWRC wires were very poor, but this is to be expected given the state of the IWRC (two wire sizes could not be tested as a sufficiently long sample could not be obtained!).

Figure 14.4: Appearance of wire failures in torsion tests on wires from the tug side sample. (Bottom OS OW1 (3 turns/100d_w), top OS CW (27 turns/100d_w)).

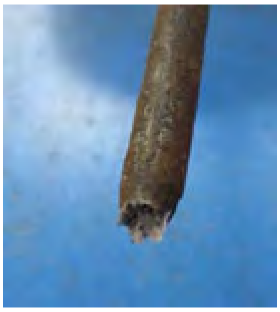
- The reverse bend tests were a little better, with about half the outer strand outer wires meeting the Standard minimum requirements. The outer strand inner wires performed well and were at a similar level to the drum sample wires. The IWRC wires performed better than in the torsion test, but the strand wires were still a little down.

Finally the bridle sample:

- The initial inspection had shown that the condition of the bridle sample was similar to that of the tug side sample. If anything the results were a little lower for the bridle sample. The outer strand outer wires were affected by surface abrasion (Figure 14.5), leading to results of 73% - 90% of the original strength. The wire rope wires from inside the outer strands which were not affected by abrasion all performed well (100% to 108%) as did the IWRC wires (100% to 104%).



OS2 OW3 - note surface abrasion



OS3 OW2

OS3 2LL

OS1 CW

Figure 14.5: Typical appearance of wire failures in tensile tests on wires from the bridle sample.

- The results of the torsion tests followed the familiar pattern - the outer strand outer wires were low, typically 10% - 30% of the standard minimum requirement. The outer strand inner layers of wires were comfortably in excess of the minimum, whilst the IWRC wires (where available) performed poorly.

Figure 14.6: Appearance of wire failures in torsion tests on wires from the bridle sample. (Bottom OS1 OW3 (3 turns/100d_w), top OS1 CW (30 turns/100d_w)).

- The reverse bend tests were a little better, with half the outer strand outer wires meeting the Standard minimum requirements. The outer strand inner wires performed well and as with the tug side sample, were at a similar level to the drum sample wires. The IWRC wires performed better than in the torsion test.

15 Results of the zinc coat weight measurement

Full sets of results for the three samples are presented in Appendix F. For ease of reference the results have been plotted in a series of bar charts (Figures 15.1 to 15.3).

With reference to Figure 15.1, in addition to the results of the tests, the chart also shows the original level (from the Manufacturer's certificate (Appendix A and Table 2.2), as well as the API 9A [**1**] Class B requirement.

It may be seen that as expected, the average coat weights on the drum sample are at the Class B requirements.

The outer wires of the outer strands of both the tug side and bridle samples are both well down. Remember that the coat weight measurement is an average figure, and does not distinguish any distribution - so a wire may be corroding on an exposed section and protected on the section towards the inside of the wire rope.

The relatively protected main strand inner layers had good levels of zinc, while the coatings on the IWRC wires were very low. These findings are in line with those of the visual inspection.

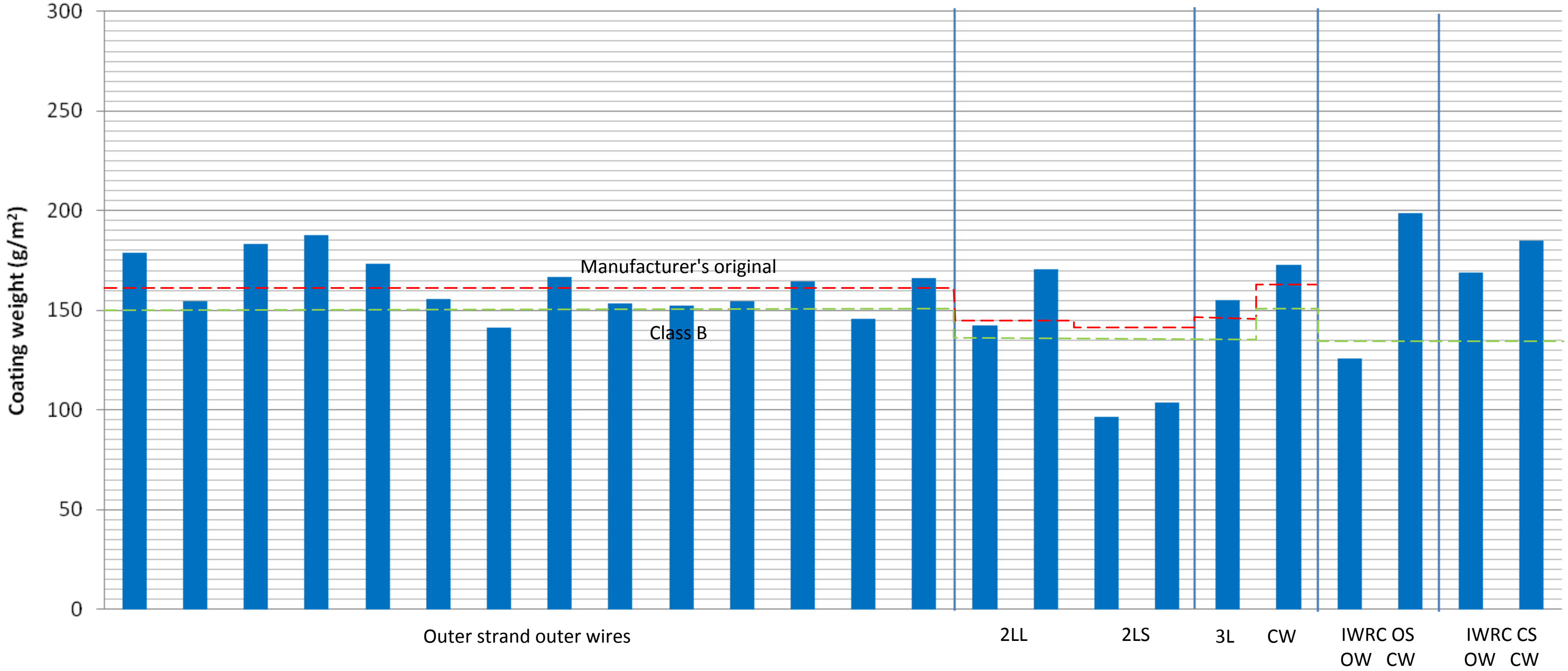


Figure 15.1: Measured average residual galvanising on wires from various positions in the wire rope construction on the drum sample.

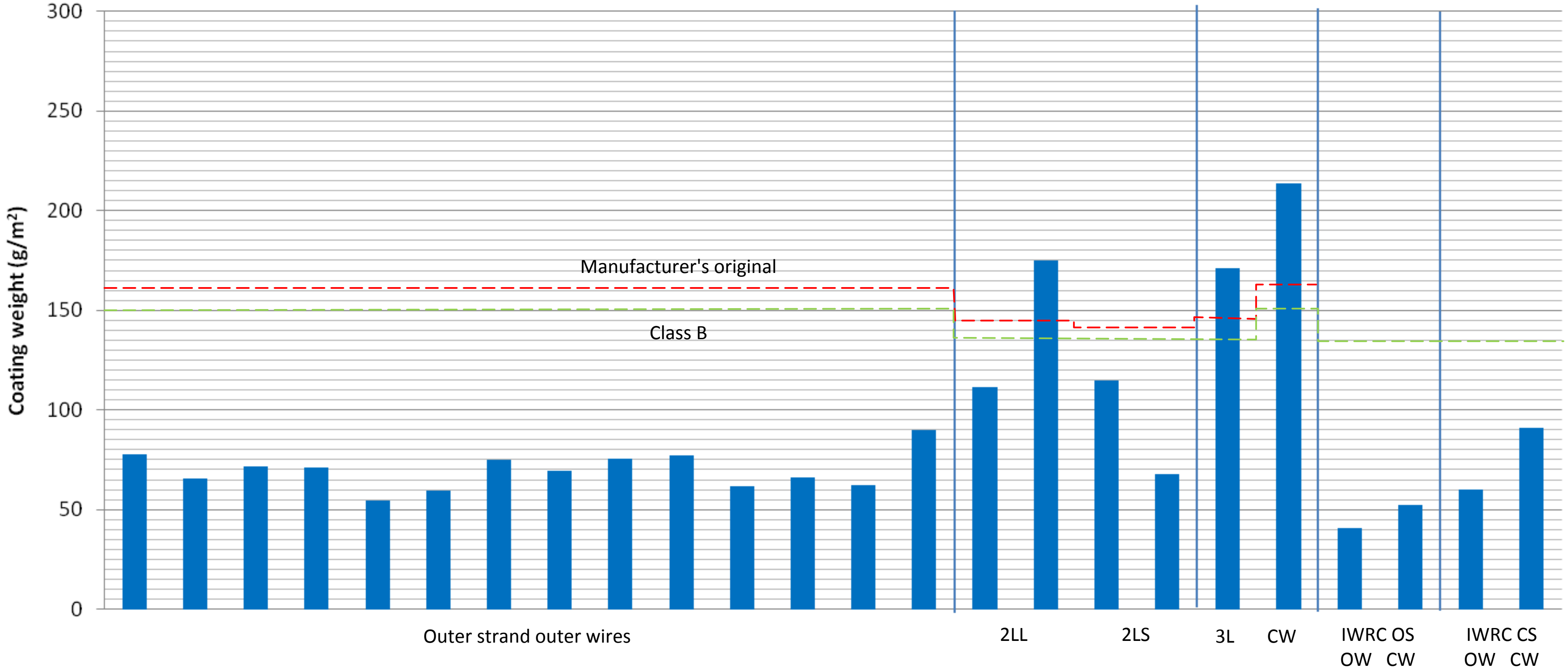


Figure 15.2: Measured average residual galvanising on wires from various positions in the wire rope construction on the tug side sample.

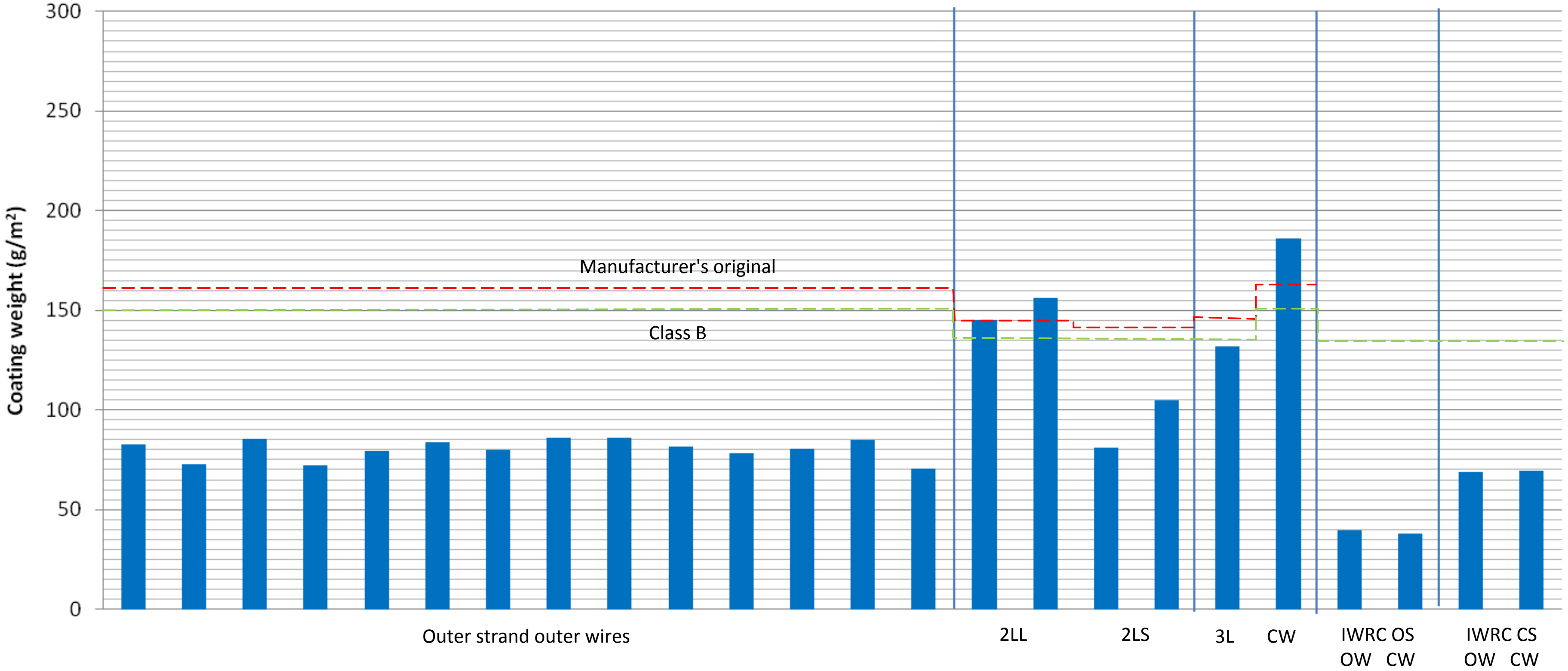


Figure 15.3: Measured average residual galvanising on wires from various positions in the wire rope construction on the bridle sample.

16 Catenary behaviour

16.1 General discussion of catenary behaviour

This section provides a general discussion on the behaviour of catenaries, and puts some approximate numbers to the situation which led to the failure of the ALP Forward's tow line. A more detailed analysis making full use of computer modelling and hindcast data etc. should be made if an accurate analysis is required.

Ractliffe and Parsey [**11**] discuss (amongst other things) the static catenary. As a very useful first approximation, it can be seen that the shape will be controlled by (Figure 16.1):

- The deployed length, *ℓ*;
- Weight per unit length of the line, *w*
- The horizontal pulling load which the (tug) is transmitting, *P*.

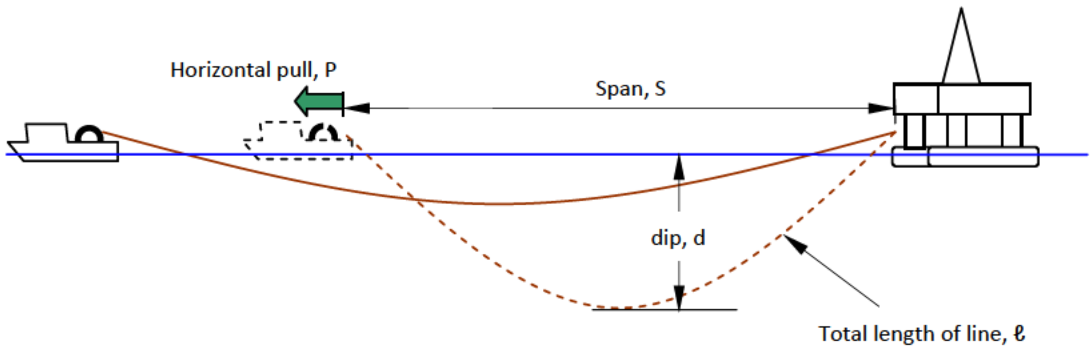


Figure 16.1: Showing the definition of terms and basic operation of a towing catenary.

Figure 16.2 below shows how the shape of the catenary varies for a range of loads. It can be seen that for any given line weight per unit length, that the higher the horizontal pull required, the smaller the dip, d. It should be noted in this Figure, as in Figure 16.1 above, that the horizontal and vertical scales are different. In Figure 16.2 the maximum value of the x-axis is 400 m, whilst for the y-axis only 180 m.

Figure 16.3 shows for the same configuration of 740 m deployed line, and for a wire rope mass of 22.9 kg/m (in water) how the tension varies as a function of the span (the vessel horizontal separation). Note how the at modest tensions the span S must change a lot to effect a change in tension, but beyond about 30 tonnes, **very** modest changes in span cause very large increases in tension. In this situation the catenary is almost flat and the loads must be accommodated by the elastic stretch of the towing line.

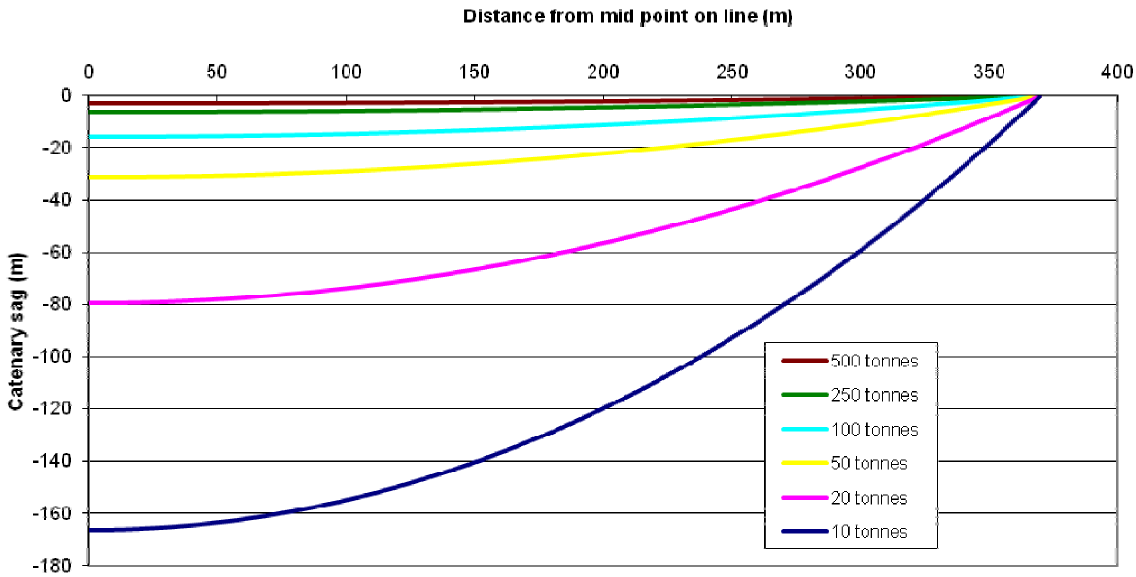


Figure 16.2: Showing for a range of loads how the catenary sag varies for a fixed line length (of 740 m) and weight per unit length (taken as 22.9 kg/m in water). Note only half the catenary has been shown as it is assumed symmetrical about the y-axis.

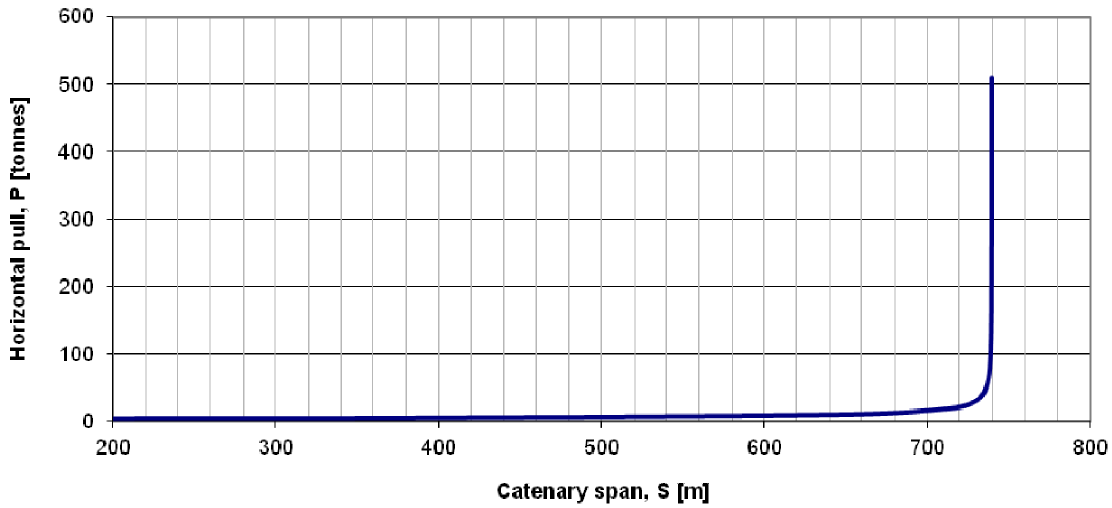


Figure 16.3: Variation in horizontal load as a function of the span (wire rope length 740 m).

This point is again emphasized by Ractliffe & Parsey [**11**] who present the following expression for the stiffness of the system, *k*, which is made up of the components of catenary stiffness $\frac{w^3 \ell^3}{12 P^3}$; and elastic stretch of the rope $\frac{w \ell}{AE}$.

$$k = \frac{w}{\frac{w \ell}{AE} + \frac{w^3 \ell^3}{12 P^3}};$$

where:

A is the nominal cross sectional area of the rope (based on the circumference).

E is the apparent Young's modulus (which for the 6×37+IWRC under discussion here is taken as 34 kN/mm^2).

The other symbols are as previously defined.

Figure 16.4 shows the ratio of the contribution of these two elements to the elasticity of the system (the inverse of stiffness) over the range of loads. As an example, at 200 tonnes (the mean load just at the time of failure [**3**], the ratio is 20.7:1, so the stretch accommodates 20.7 times as much of the elongation as the change in catenary shape. It can clearly be seen; that for the towing application, especially at the loads we are interested in, the dominant factor is the elastic stretch of the line.

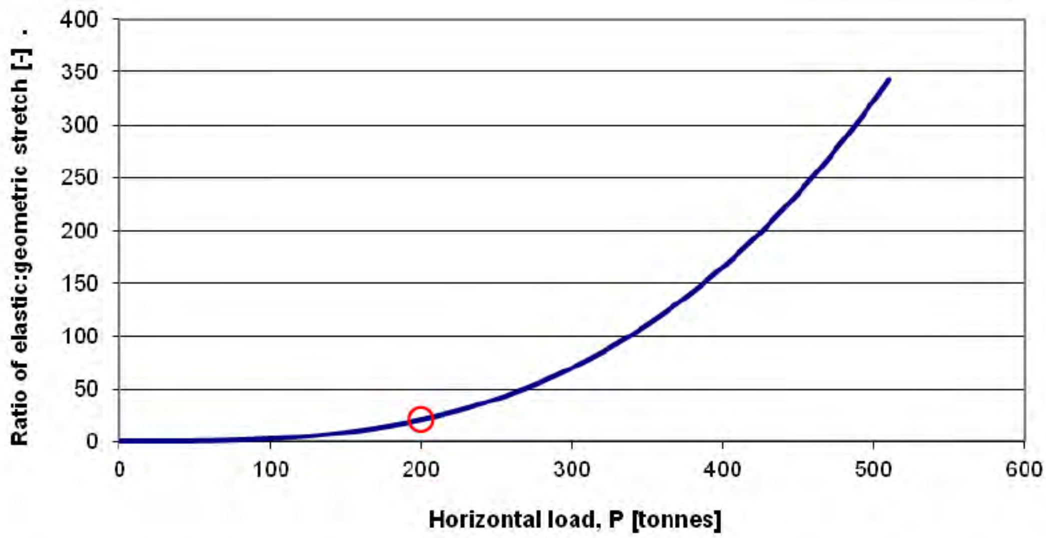


Figure 16.4: Ratio of the contributions of elastic : geometric stretch for a range of loads. The red circle shows the point for 200 tonnes horizontal load, where curve shows that the ratio is 20.7:1.

16.2 Approximate calculation of maximum loads in the towing wire rope

An approximate calculation of peak loads in the wire rope may be performed by undertaking the following steps:

- Characterising the towing wire rope load-extension behaviour;
- Definition of the model; and then,
- Calculating the wire rope loads imposed for a given stretch

16.2.1 Characterisation of the wire rope

Figure 16.5 below is taken from the breaking load test undertaken on the drum sample (Appendix C). For all practical purposes, the slope of this line will be assumed constant over the range of loads of interest.

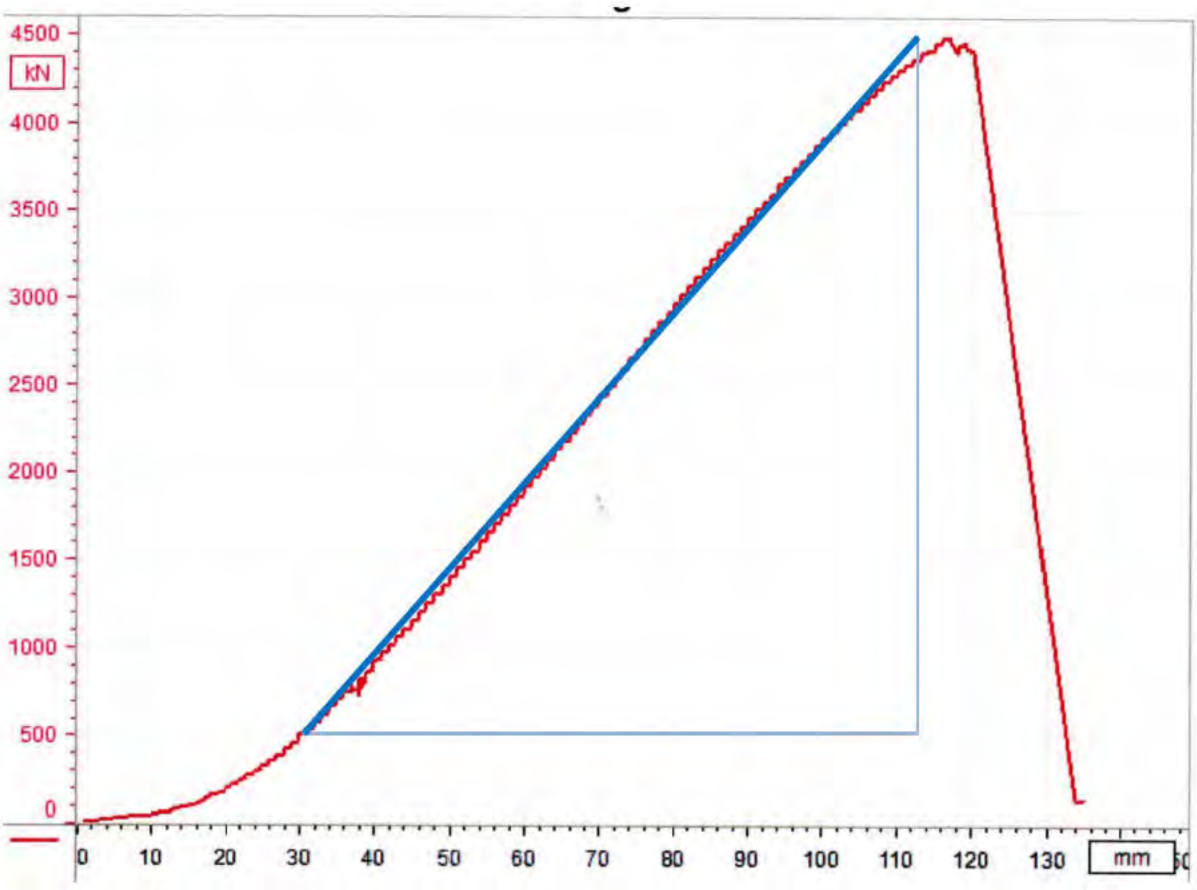


Figure 16.5: Load-extension measurements for the drum sample (77 mm 6×37 + IWRC RHO) during the breaking load test (3190 mm long).

Young's modulus E is defined as: $E = \dfrac{\Delta F / A}{\Delta \ell / \ell}$

Where: ΔF is the change in (wire rope force);

A is the nominal wire rope area;

ℓ is the initial length of the sample; and,

$\Delta\ell$ is the change in length caused by the change in load (ΔF)

Re-arranging this equation gives:

$$EA = \left(\frac{\Delta F}{\Delta \ell}\right) \cdot \ell$$

In this equation the term $\Delta F/\Delta\ell$ is the slope on the graph (shown by the blue line in Figure 16.5). The slope of the blue line in Figure 16.5 is 49.8 kN/mm and the length ℓ is 3190 mm, which gives a value of **EA of 159 MN**.

16.2.2 Definition of the model

Re-arranging the equation above gives: $\Delta F = \dfrac{\Delta \ell \cdot EA}{\ell}$.

- EA = 159 MN (characteristic wire rope axial stiffness)
- ℓ = the length of wire rope paid out,
- Assuming that *ALP Forward* and *Transocean Winner* are forced apart by wave motions, and that the required stretch in the wire rope to accommodate the movement apart $\Delta\ell$, is determined by the significant wave height H_s (i.e. $\Delta\ell = H_s$).

This permits calculation of the *change in force* ΔF caused by the sudden wave imposed movement $\Delta\ell$.

Hence the maximum load in the wire rope is the change in load + the initial load

It is again noted that this calculation is approximate, but does give an idea of the levels of load which might have been experienced in the wire rope during the storm.

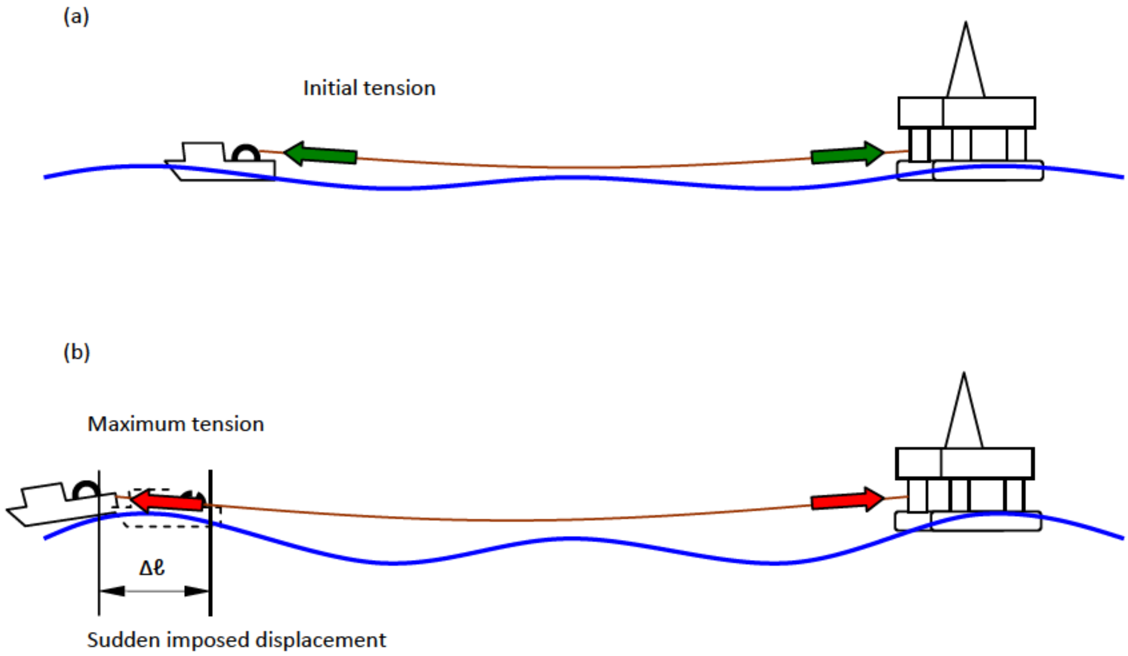


Figure 16.6: Definition of the model for the loads in the towing line.

16.2.3 Calculation of peak loads

In the following analysis three scenarios will be considered:

1. *ALP Forward* had 568 m wire rope deployed with initial tension of 120 tonnes in seas of H_s = 8.4 m (Table 4.3 [**12**] 7th August 2016 13:00 UTC);
2. *ALP Forward* had 568 m wire rope deployed with initial tension of 120 tonnes and experienced an individual maximum wave height of 16.8 m (§7.2 [**12**]) (7th August 2016); and,
3. *ALP Forward* had 740 m wire rope deployed with seas of 5.8 m (Table 4.3 [**12**] 8th August 2016 01:00 UTC) and initial tension of 220 tonnes (tension at 03:20 UTC - time of failure on the 8th August 2016).

Table 16.1 summarises the calculated maximum loads experienced by the wire rope for each of these scenarios.

It may be seen that the calculation predicts some very high loads - which raises the question of whether the winch would have rendered. The rendering of the winch will be affected by many variables such as condition and set up, as well as the inertia of the system which will affect how quickly if could respond to the applied load.

	Scenario 1	Scenario 2	Scenario 3
scope [m]	568	568	740
$H_s = \Delta l$ [m]	8.4	16.8	5.8
initial load [tonnes]	120	120	220
EA [MN]	159	159	159
ΔF [tonnes]	240	479	127
Peak tension [tonnes]	**360**	**599**	**347**

Table 16.1: Approximate calculation of peak tensions experienced by the wire rope.

16.3 Fatigue loading

Another factor which should be considered is that the prolonged exposure of the wire rope to significant varying loads during the storm will have inevitably caused some reduction in endurance through fatigue. API RP 2SK [**13**] provides guidance for calculating the nominal tension fatigue life of wire ropes of the size and construction under consideration here.

$$N = \frac{K}{R^M}$$

where:

N = Number of cycles

R = Ratio of tension range to rope MBL

M = 4.09 for six strand rope

K = $10^{(3.20 - 2.79Lm)}$

Lm = Ratio of mean load to rope MBL

Figure 16.7 shows the predicted number of cycles to failure for a rope loaded from zero to peak tension (the load range) for varying load ranges. By way of example, it may be seen that for a peak tension of 240 tonnes, the predicted number of cycles to failure would be 5,745 cycles. At a period of 14 s, failure would occur after about 22 hours.

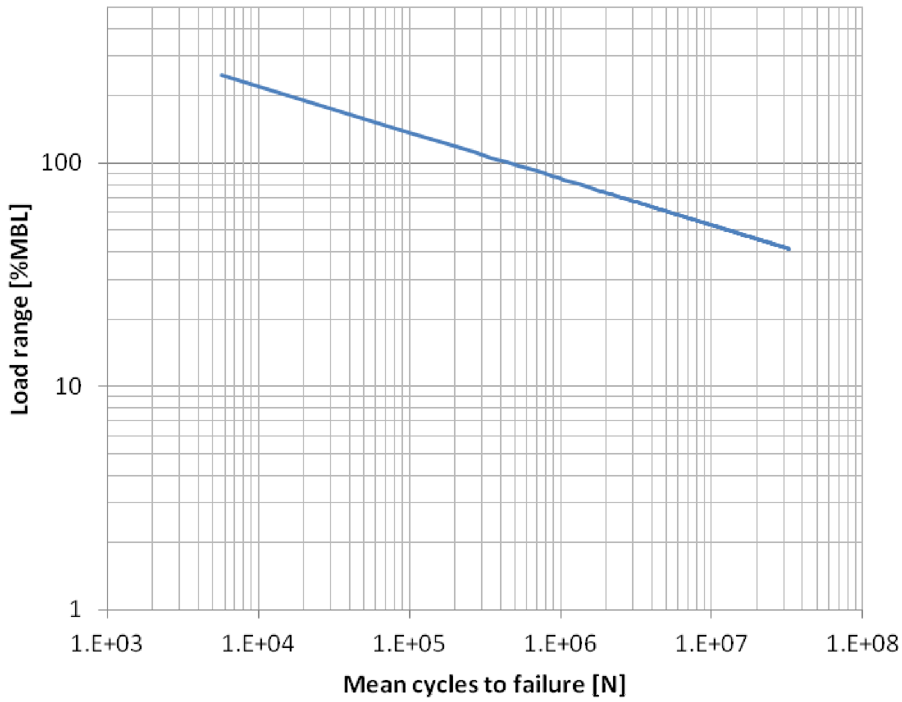


Figure 16.7: Mean cycles to failure as a function of load range based on API RP 2SK [**13**].

17 Discussion and Conclusions

This report has described the inspection and testing of a number of sections of the failed wire rope from the tug ALP Forward.

As well as visual inspection, samples have been taken for breaking load testing and mechanical testing of the wires.

Inspection of the tug side and bridle samples indicated that the samples were in a similar condition. The IWRC was generally in a very poor state with many wire breaks (typically 100+ in a 1 m length). The IWRC represents about 15% of the metallic cross sectional area, and so it was to be expected that the breaking load samples would be at least 15% down on the original value, and a bit more owing to the broken outer strand wires.

The loss of strength due to the core disintegration was one issue, but another problem is that the damaged core was unable to provide proper support to the outer strands. As the core collapsed, so the outer strands contacted one another leading to a series of breaks in the strand valley positions (see Figures 9.10, 10.42 and 17.1). It is noted that the outer strand outer wires represent about 44% of the metallic sectional area in the wire rope (so each wire is roughly 0.5% of the total area).

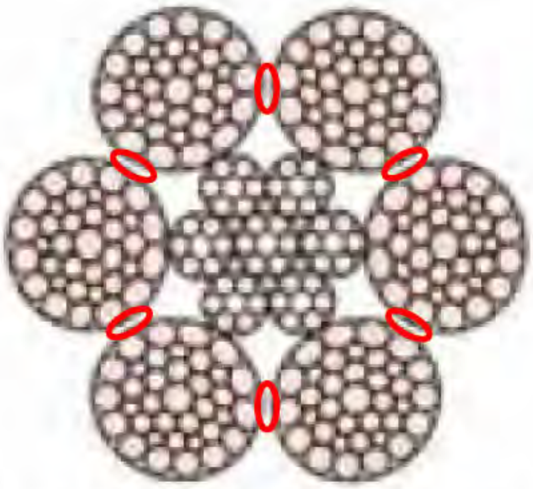


Figure 17.1: Wire rope (6 × 37 + IWRC 'Super Titan') cross-section showing inter strand contact positions exacerbated by an incorrect size (small) or damaged/worn core.

The results of the breaking load tests showed that the strength of the wire rope tug side and bridle side was down by 21.3% (tug side sample) and 23.5% (bridle sample) on the original measured strength.

The results of the mechanical tests on the wires from the drum sample show that the wire stock from which the wire rope was made satisfied the requirements of the Standard API 9A [1]. The wires inside the main load bearing strands (second and third layers and core wires) of the tug and bridle samples have largely retained their properties, whilst the outer wires and core wire have suffered as mentioned above.

It is considered that the outer strand outer wires have additionally been affected by the onset of corrosion - the lubricant was generally missing or low/denatured. It is noted that had the wire rope been assessed under the criteria of ISO 4309:2010 [**5**], then it would have been subject to immediate discard.

In fact the condition of the wire rope is so poor as to raise the question of its condition when last inspected in July 2016 [**4**]. It is noted that the wire rope was re-socketed in July 2016 - given the condition of the bridle sample IWRC when terminated for break test, it might prove informative to remove and examine the spelter socket on the wire rope.

Turning to consider the sorts of loads which the wire rope might have experienced during the storm, an approximate calculation assuming a maximum wave height of 16.8 m indicates a load of the order of 599 tonnes. This load is well in excess of the measured tug side sample BL of 389 tonnes, and above the wire rope F_{min} (485 tonnes) and the measured ABL of 494.1 tonnes. Given this estimate, it is not surprising the wire rope failed. It is quite possible that the wire rope would have failed even if it had been as new.

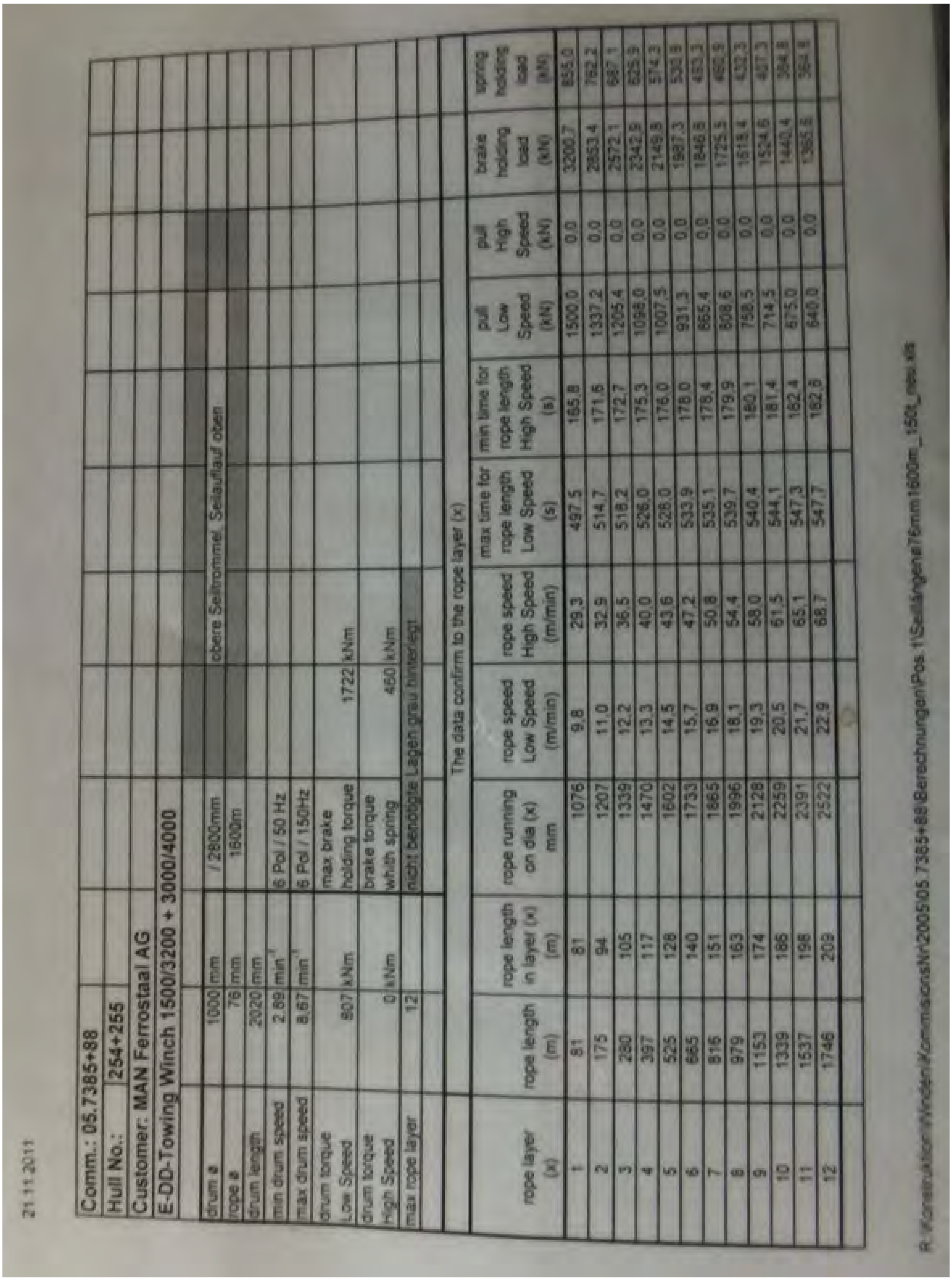
It is noted that the load stated above assumes that the winch drum would not have slipped or rendered. Details of the winch drum are not known, but a data sheet (Figure 17.2) indicates that with 740 m paid out the brake holding load was about 1725 kN or 176 tonnes. It has been reported that the winch had been rendering and loads of 180 - 220 tonnes had been recorded [**3**]. It is possible that a shock load might be applied to the wire rope so quickly that the drum did not have time to accelerate.

In addition to setting the winch to render, another option to help manage the loads on the wire rope would be to extend the scope of the towing line. Whilst it is not ideal to drag a wire rope along the seabed, in cases of extreme need it would be preferable to do this so as to help avoid breaking the line.

In conclusion, this study has shown that the 77 mm wire rope installed on the *ALP Forward* in May 2014 satisfied the requirements of API 9A [**1**]. Although the tow wire log [**4**] states that the line is regularly washed and greased during recovery, it is far from clear that this process is effective - the lubricant on the tug side and bridle samples were very low and the wire rope has started to corrode. (Generally speaking it is preferable to avoid re-greasing a wet wire rope as this can trap moisture in the wire rope accelerating corrosion. It is possible that this has happened to the wire rope examined here.) The condition of the core was very poor.

It is likely that the rope had become further degraded through fatigue damage during the earlier part of the storm, and finally broke due to a one off overload.

Breaking load tests on sections of wire rope from either side of the main failure suggest that at the time of the incident the wire rope strength was down by 21.3% to about 389 tonnes.



21.11.2011

Comm.: 05.7385+88					
Hull No.:	254+255				
Customer: MAN Ferrostaal AG					
E-DD-Towing Winch 1500/3200 + 3000/4000					
drum ø	1000	mm	/ 2800mm		obere Seiltrommel, Seilauflauf oben
rope ø	76	mm	1600m		
drum length	2020	mm			
min drum speed	2,89	min⁻¹	6 Pol / 50 Hz		
max drum speed	8,67	min⁻¹	6 Pol / 150Hz		
drum torque Low Speed	807	kNm	max brake holding torque	1722	kNm
drum torque High Speed	0	kNm	brake torque whith spring	460	kNm
max rope layer	12		nicht benötigte Lagen grau hinterlegt		

The data confirm to the rope layer (x)

rope layer (x)	rope length (m)	rope length in layer (x) (m)	rope running on dia (x) mm	rope speed Low Speed (m/min)	rope speed High Speed (m/min)	max time for rope length Low Speed (s)	min time for rope length High Speed (s)	pull Low Speed (kN)	pull High Speed (kN)	brake holding load (kN)	spring holding load (kN)
1	81	81	1076	9,8	29,3	497,5	165,8	1500,0	0,0	3200,7	855,0
2	175	94	1207	11,0	32,9	514,7	171,6	1337,2	0,0	2853,4	762,2
3	280	105	1339	12,2	36,5	518,2	172,7	1205,4	0,0	2572,1	687,1
4	397	117	1470	13,3	40,0	526,0	175,3	1098,0	0,0	2342,9	625,9
5	525	128	1602	14,5	43,6	528,0	176,0	1007,5	0,0	2149,8	574,3
6	665	140	1733	15,7	47,2	533,9	178,0	931,3	0,0	1987,3	530,9
7	816	151	1865	16,9	50,8	535,1	178,4	865,4	0,0	1846,8	493,3
8	979	163	1996	18,1	54,4	539,7	179,9	808,6	0,0	1725,5	460,9
9	1153	174	2128	19,3	58,0	540,4	180,1	758,5	0,0	1618,4	432,3
10	1339	186	2259	20,5	61,5	544,1	181,4	714,5	0,0	1524,6	407,3
11	1537	198	2391	21,7	65,1	547,3	182,4	675,0	0,0	1440,4	384,8
12	1746	209	2522	22,9	68,7	547,7	182,6	640,0	0,0	1365,8	364,8

R:\Konstruktion\Winden\KommisionsNr\2005\05.7385+88\Berechnungen\Pos.1\Seillängenø76mm1600m_150t_neu.xls

Figure 17.2: ALP Forward main winch data sheet (supplied by MAIB).

18 References

1 **API 9A** Specification for wire rope, 26th edition, May 2011, Reaffirmed April 2016, published American Petroleum Institute.

2 **Usha Martin** *Wire Rope Hand Book* Published by Usha Martin (ushamartin.com) p75.

3 Pers. Comm. data supplied by MAIB (Capt. Emma Tiller) in .xls spread sheet 'Towline'.

4 **ALP Maritime Services**, Main tow-wire log .xls spread sheet forwarded by MAIB file name 'Updated Tow Wire Record Alp Forward.xls'.

5 **BS ISO 4309:2010** *Cranes – wire ropes – care and maintenance, inspection and discard*, International Standards Organisation, 4th Edition, August 2010, ISBN: 978 0 580 59980 4.

6 **BS EN 10264-2:2012** *Steel wire and wire products – Steel wire for ropes Part 2: Cold drawn non alloyed steel wire for ropes for general applications*, British Standards Institution, 2012.

7 **ISO 10425:2003** *Steel wire ropes for the petroleum and natural gas industries – minimum requirements and terms of acceptance,* International Standards Organisation, August 2003.

8 **ISO 7800:2012** *Metallic materials – Wire – Simple torsion test*, International Standards Organisation, March 2012.

9 **ISO 7801:1984** *Metallic materials – Wire – Reverse bend test*, International Standards Organisation, May 1984.

10 **BS EN 10244-1:2001** *Steel wire and wire products – non-ferrous metallic coatings on steel wire – Part 1: General principles,* British Standards Institution, 2001.

11 **Ractliffe, A.T. and Parsey, M.R.** Man-made-fibre ropes for marine use, Trans North East Coast Institution of Engineers and Shipbuilders (NECIES) 101 (1985) pp 183-197.

12 **Stretch, R.** *Met Office Marine Weather Data report compiled for MAIB* Reference msc/08/16/056, 30th August 2016, §7.2.

13 **API RP 2SK** Design and analysis of stationkeeping systems for floating structures, 3rd edition October 2005, Addendum 2008, published American Petroleum Institute.

Appendices

Appendix A - Tow wire inspection certificate

Ref: VIS 410

Ord. No. :41213022

DNV

DET NORSKE VERITAS

CERTIFICATE

This is to certify that the undersigned Surveyor of this Society, at the request of M/s.Usha Martin Limited, Kolkata, did attend their Works at Ranchi on 26th of March'2013 to inspect Wire ropes as stated below :

Purchaser	:	USHA MARTIN UK LIMITED - EMMC.
Purchase Order Reference	:	EMM0229 Dated 11.01.2013
Manufactured By	:	M/S.USHA MARTIN LIMITED Wire ropes & Speciality products Division. TATISILWAI WORKS, RANCHI
Work Order No.	:	944823/7 Dated 12.01.2013
Specification	:	API-9A/2011 in general
Wire Rope Details	:	77 mm dia(Mbl- 485 mt) galvanised Steel Wire Rope 6x36 + IWRC , STITN, Preformed, RHO with "D" lubrication.
Applied Load on Representative sample	:	496.0 mt
Quantity	:	2/3000 Mtrs in Reel No. 163288/1-2
Test Results	:	Manufacturer's Inspection Certificate No. I 163288/1-2
Visual Examination	:	Satisfactory

The rope presented was found to satisfy the requirements of the specification with wire rope breaking load obtained from representative sample. The rope was sealed with mark on Metal Tag at one end.

[redacted]

29.03.2013

DET NORSKE VERITAS 1864 VISAKHAPATNAM

[redacted]

Surveyor

Lloyd's Register

[redacted]

28-6-13

If any person suffers loss or damage which is proved to have been caused by any negligent act or omission of Det Norske Veritas, then Det Norske Veritas shall pay compensation to such person for his proved direct loss or damage. However, the compensation shall not exceed an amount equal to ten times the fee charged for the service in question, provided that the maximum compensation shall never exceed USD 2 million. In this provision "Det Norske Veritas" shall mean the Foundation Det Norske Veritas as well as all its subsidiaries, directors, officers, employees, agents and any other acting on behalf of Det Norske Veritas.

DET NORSKE VERITAS, VERITASVEIEN 1, N-1322 HØVIK, NORWAY, TEL INT +47 67 57 99 00, TELEFAX +47 67 57 99 11

Form No. 40.91a Issue: July 99

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usha martin

Usha Martin Limited
(Wire Ropes & Speciality Products Division)
Works : Tatisilwai - 835 103, Ranchi, Jharkhand
Ph.: (00 91 651) 3051400 / 2265241
Fax : (00 91 651) 3051409 / 410

INSPECTION CERTIFICATE

F/QP-2-17/33R Rev:1

Certificate Number	: I 163288/ 2	Date:22-03-2013
Customer	: USHA MARTIN UK LIMITED - EMMC	
Customer Order Ref	: EMM0229	Date:11-01-13
Works Order Number	: 944823/ 7	Date:12-01-13
Reel Number	: 163288/2 (SS No:15)	Date of Test:22-03-13
Manufacturer	: USHA MARTIN LIMITED , INDIA	

SPECIFICATION

Applied Standard	: Generally in accordance with API-9A/2011
Nominal Diameter of Rope	: 77 mm
Construction	: 6X36
Strand Construction	: 14-7+7-7-1 , Preformed
Tensile Grade of Steel Wire	: SUPER TITAN
Wire Finish/Material Grade	: Galvanized
Type of Core/Lay Direction	: IWRC / RHO
Length of Rope	: 3000.00 Mtr
Mass/Unit Length (Apprx.)	: 25.013 Kg/Mtr
Lubrication	: D / Bitumin Lube
Minimum Breaking Force	: 485.0 mt

RO8014

RESULTS OF TEST & EXAMINATION

Measured Dia. Off-tension	: 78.460 mm
Measured Lay Off-tension	: 534.00 mm
Measured Breaking Force	: 494.1 mt

INDIVIDUAL WIRE TESTS

Sl. No.	Wire Dia	Tensile Strength (Avg)	Bend (Avg)	Torsion (Avg)	Knot Test	Wt.of Zinc Coating (Avg)
1	4.39 mm	2164 N/sq.mm	NA	13	NA	161 g/sqm
2	2.73 mm	2096 N/sq.mm	NA	23	NA	142 g/sqm
3	3.53 mm	2128 N/sq.mm	NA	17	NA	146 g/sqm
4	3.62 mm	2075 N/sq.mm	NA	16	NA	145 g/sqm
5	4.81 mm	2087 N/sq.mm	NA	12	NA	163 g/sqm

CHEMICAL ANALYSIS OF WIRE ROD

Sl.	Wire Dia	Carbon%	Manganese%	Silicon%	Sulphur%	Phosphorus%
1	4.39 mm	0.880	0.780	0.190	0.014	0.020
2	2.73 mm	0.870	0.700	0.240	0.017	0.019
3	3.53 mm	0.880	0.810	0.240	0.014	0.020
4	3.62 mm	0.880	0.830	0.260	0.016	0.011
5	4.81 mm	0.870	0.720	0.200	0.0 3	0.019

This is to certify that the above tests have been carried out in accordance with the Speicification

[redacted]

28-6-13

in Jadav
r (QA)
imited
hand

[redacted]
Signature of Competant Person

Lloyd's Register — Certified as an Approved Manufacturer by Lloyd's Register of Asia

DNV — Certified as an approved Manufacturer by Det Norske Veritas

API — Certified by the American Petroleum Institute License number 9A-0017

ABS — Type Approval Program — Certified as an Approved Manufacturer by American Bureau of Shipping

Certified for the Quality Management System to ISO 9001 : 2008 & ISO 14001 : 2004 Bureau Veritas Certification

Regd. Office : 2A Shakespeare Sarani, Kolkata 700 071, India, Phone : (00 91 33) 39800300/22823985, Fax : (00 91 33) 2282 5306/9029/3980 0500/0400

F/QP-3-145/01 Rev 0

Appendix B - Calibration certificate for the 14,000 kN test machine

NMi

CERTIFICATE

number 16203457.1001.2EN/R1
page 1 of 6

Applicant	Mennens Dongen BV Metaalstraat 5 5107 ND DONGEN Nederland
Investigated	Tension testing machine for chains manufacturer : J.G. de Haan - Musselkanaal type : 14000 kN identification : 39388 kind of drive : Electric hydraulic capacity : 14000 kN
Range(s)	The calibration has been executed from 300 up to and including 14000 kN.
Test method	Comparison of the load indication with calibration standards in accordance with the procedures laid down in EN-ISO 7500-1.
Ambient Temp.	(18.6 ± 0.5)°C
Test Date	The test was performed on October 24th 2016.
Conclusion	The accuracy of the load indication meets the requirements according to ISO 1834, with a lower limit of 300 kN.
Result	The result is shown on the next page(s).
Traceability	The measurements have been executed using standards that are traceable to primary and/or (inter)national standards.
Location	Workshop of Mennens Dongen B.V. - Dongen
Indication	Electronic Egeay compression loadcell no 13 - 13550 kN MPA no 2879 with a siemens siwarex U amplifier and a personal computer with force indication on the monitor.
Adjustments	The investigation has been executed after adjustment. The values measured prior to the adjustment have been displayed on the last pages.

NMi Certin B.V.

[redacted]

Head Certification Board

pt-001 2009-01-01
Dum, A.R. van

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This document is issued under the provision that no liability is accepted and that the applicant shall indemnify third-party liability.

CALIBRATION
RvA K 183

CERTIFICATE

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Deviations	q_{max} = 0.2% of F_A b_{max} = 0.7% of F_A $F_{0,max}$ = 0.0% of F_N
Resolution	a ≤ 0.3 % of the lower limit.
Uncertainty	Force 0.25 % of F_{Wi} The reported uncertainty is based on a standard uncertainty multiplied by a coverage factor of k = 2, which provides a confidence level of approximately 95 %. The standard uncertainty has been determined in accordance with EA-4/02.
Used standards	23010261 Measuring amplifier HBM DK38 nr.46546 53000854 Thermometer 23010006 Load cell T06 16MN

CERTIFICATE

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SYMBOLS AND DEFINITIONS FOR THE CALIBRATION OF TENSILE AND COMPRESSION TESTING MACHINES

F_N	Maximum capacity of a measuring range of the force indicator of the testing machine in N
F_A	Force reading on the indicator with increasing test force in N
F_C	True force indicated by the calibration device in mV/V
F_W	True force calculated from F_C in N
F_{A1}, F_{C1}, F_{W1}	As F_A, F_C and F_W with decreasing force
F_{Amax}, F_{Amin}	Highest and lowest values of F_A
F_{Wmax}, F_{Wmin}	Highest and lowest values of F_W
F_{A0}	Residual indication on the force indicator after removal of the force
F_{Ad}	Force indication after 15 min. unloaded (drift of electronic measuring equipment)
A_r	Resolution of the force indicator in N (smallest possible value to be estimated)
q	Relative accuracy error of the indicated force $\frac{F_A - F_W}{F_W} \times 100\%$
b	Relative repeatability error $\frac{F_{Wmax} - F_{Wmin}}{F_W} \times 100\%$
u	Relative reversibility error $\frac{F_W - F_{W1}}{F_W} \times 100\%$ (the reversibility error is only determined on request)
a	Resolution at the lower limit of the range $\frac{A_r}{F_W} \times 100\%$
r	Resolution $\frac{A_r}{F_N} \times 100\%$
f_0	Relative error at zero $\frac{F_{A0}}{F_N} \times 100\%$
f_d	Drift of zero within 15 min $\frac{F_{Ad}}{F_N} \times 100\%$ (due to possible drift within the electronic measuring equipment)

CERTIFICATE

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REQUIREMENTS FOR CALIBRATION OF UNIAXIAL TESTING MACHINES

Tensile testing machines for metals according to EN-ISO 7500-1

Class of testing machine	Maximum permissible value in each range in %				
	q	b	u	a	f_0
0.5	± 0.5	0.5	0.75	0.25	± 0.05
1	± 1.0	1.0	1.5	0.5	± 0.1
2	± 2.0	2.0	3.0	1.0	± 0.2
3	± 3.0	3.0	4.5	1.5	± 0.3

Tensile testing machines for chains according to EN 818-1
Tensile testing machines for chains according to ISO 1834;
maximum permissible error q ± 1.5%

NMi

CERTIFICATE

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Range 14000 kN

Table 1. Tensile load after adjustement

$F_{A,1}$ kN	$F_{A,2}$ kN	$F_{A,3}$ kN	F_A kN	$F_{W,1}$ kN	$F_{W,2}$ kN	$F_{W,3}$ kN	F_W kN	q %	b %
313.00	313.00	308.00	311.33	314.32	312.02	307.63	311.32	0.0	0.7
505.00	524.00	508.00	512.33	505.55	523.62	505.93	511.70	0.1	0.5
1014.0	1011.0	990.00	1005.0	1014.6	1012.9	989.50	1005.6	-0.1	0.2
2160.0	2132.0	2113.0	2135.0	2164.4	2131.0	2111.7	2135.7	0.0	0.3
3027.0	3101.0	3122.0	3083.3	3028.7	3099.2	3121.0	3083.0	0.0	0.1
4116.0	4026.0	4022.0	4054.7	4116.5	4033.9	4029.9	4060.1	-0.1	0.2
5127.0	5068.0	5070.0	5088.3	5131.6	5068.8	5070.1	5090.2	0.0	0.1
5984.0	6077.0	6038.0	6033.0	5990.3	6083.5	6036.1	6036.6	-0.1	0.1
7010.0	7052.0	7017.0	7026.3	7012.4	7059.5	7027.6	7033.1	-0.1	0.1
8064.0	8014.0	7960.0	8012.7	8057.1	8002.4	7945.4	8001.6	0.1	0.1
9040.0	9022.0	8943.0	9001.7	9015.0	9002.0	8925.5	8980.9	0.2	0.1
10103	10043	10110	10085	10081	10028	10089	10066	0.2	0.1
11012	11049	11112	11058	11009	11050	11103	11054	0.0	0.1
12077	12048	12034	12053	12060	12032	12007	12033	0.2	0.1
13071	13021	13003	13032	13059	13015	12985	13020	0.1	0.1
14108	14138	14000	14082	14121	14149	13997	14089	-0.1	0.1
-1.0000	-3.0000	-1.0000	-3.0000				0		

CERTIFICATE

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Range 14000 kN

Table 2. Tensile load before adjustement

$F_{A,1}$ kN	$F_{A,2}$ kN	$F_{A,3}$ kN	F_A kN	$F_{W,1}$ kN	$F_{W,2}$ kN	$F_{W,3}$ kN	F_W kN	q %	b %
293.00	306.00	310.00	303.00	297.94	308.94	312.94	306.61	-1.2	0.7
521.00	532.00	554.00	535.67	531.85	541.92	563.75	545.84	-1.9	0.3
1027.0	1025.0	1032.0	1028.0	1038.5	1034.5	1034.3	1035.8	-0.8	0.9
2030.0	2041.0	1990.0	2020.3	2045.2	2052.8	1995.4	2031.1	-0.5	0.5
3011.0	2986.0	3017.0	3004.7	3026.6	2999.2	3021.6	3015.8	-0.4	0.4
4003.0	3998.0	4158.0	4053.0	4020.5	4009.4	4166.3	4065.4	-0.3	0.2
5031.0	5034.0	5027.0	5030.7	5049.6	5045.5	5031.2	5042.1	-0.2	0.3
5979.0	5972.0	5982.0	5977.7	5999.1	5987.0	6002.0	5996.0	-0.3	0.1
7038.0	6990.0	7068.0	7032.0	7055.9	7010.6	7081.3	7049.3	-0.2	0.1
7999.0	8034.0	8029.0	8020.7	8018.4	8057.4	8039.8	8038.5	-0.2	0.2
8980.0	9045.0	9026.0	9017.0	9011.2	9068.9	9050.0	9043.4	-0.3	0.1
10031	10074	10114	10073	10060	10099	10136	10099	-0.3	0.1
11030	10953	11044	11009	11085	10999	11089	11058	-0.4	0.1
12007	12019	12024	12017	12068	12070	12071	12070	-0.4	0.1
13023	13000	13150	13058	13076	13054	13211	13114	-0.4	0.1
14208	14155	14245	14203	14231	14185	14272	14229	-0.2	0.0
-3.0000	2.0000	-5.0000	-5.0000				0		

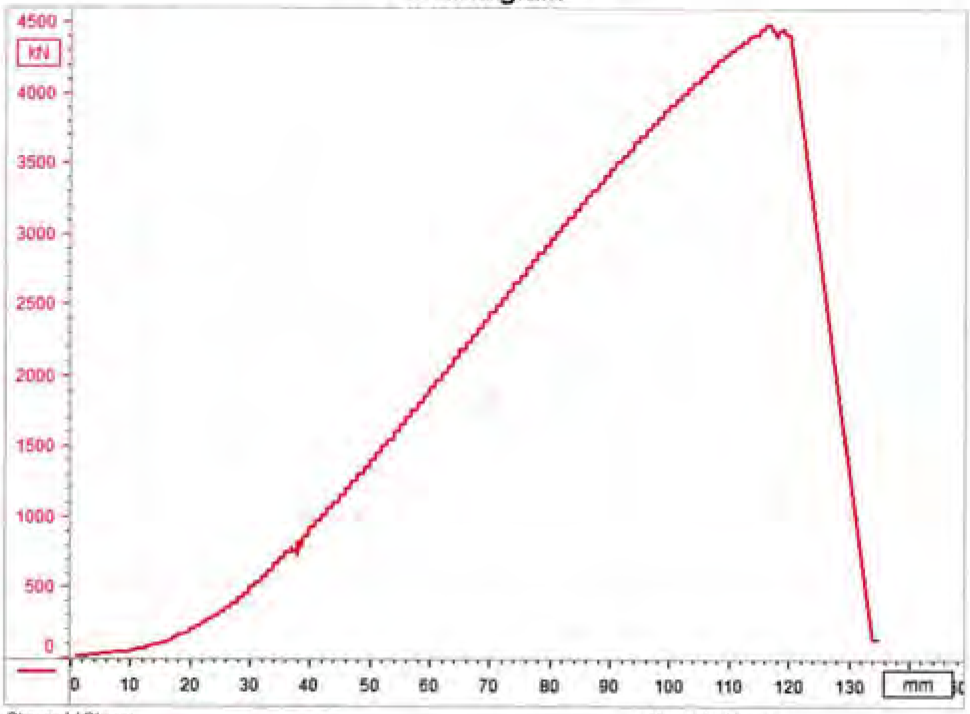
Appendix C - Certificates for the break load tests

MENNENS

Klant / Customer	TTI Testing	Omschrijving / Description	
Order / Order	748836	Breakload test steel wire rope 77mm	
Object / Object	Steel wire rope 77mm		
		Opmerkingen / Remarks	
Serie nr. / Serial No.		5M section from alp forward winch drum	
Proeftype / Type of test	Breekproef		
Proef / Test	0 van / of 0	Starttijd /Time started	24-11-2016 09:29:35
Datum / Date	24.11.2016	Stoptijd /Time stopped	24-11-2016 09:37:21

Hoogste Kracht / Highest Force	4493	kN	Stijgtijd / Rising time 500	kN/Min
Hoogste Rek/ Highest Elasticity	139	mm		

F-E Diagram



Stempel / Stamp

[redacted]

Stempel / Stamp

Mennens Dongen B.V.
Metaalstraat 5
5107 ND DONGEN
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Telefax: 0031 (0) 162-32 30 80
E-mail: info@proofloadtesting.com
Internet: www.proofloadtesting.com

Part of AXLOAD

MENNENS

Klant / Customer	TTI Testing
Order / Order	748836
Object / Object	Steel wire rope 77mm
Serie nr. / Serial No.	
Proeftype / Type of test	Breekproef
Proef / Test	0 van / of 0
Datum / Date	24.11.2016

Omschrijving / Description

Breakload test steel wire rope 77mm

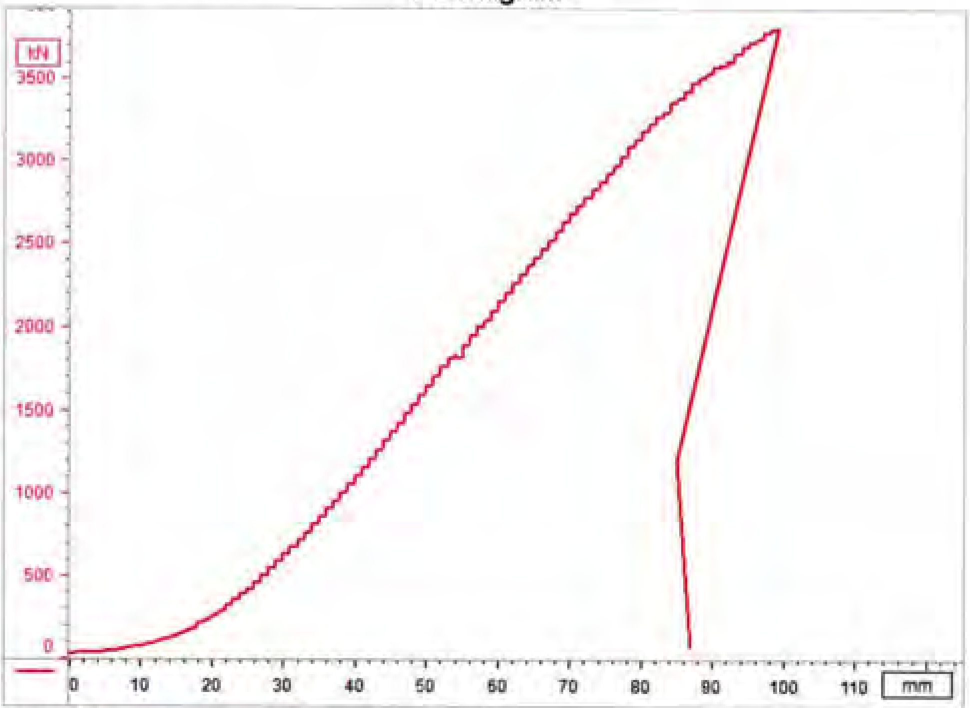
Opmerkingen / Remarks

5M section alp forward side sample

Starttijd /Time started	24-11-2016 11:21:00
Stoptijd /Time stopped	24-11-2016 11:26:08

Hoogste Kracht / Highest Force	3815	kN	Stijgtijd / Rising time	500	kN/Min
Hoogste Rek/ Highest Elasticity	115	mm			

F-E Diagram



Stempel / Stamp

[redacted]

Stempel / Stamp

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Internet: www.proofloadtesting.com

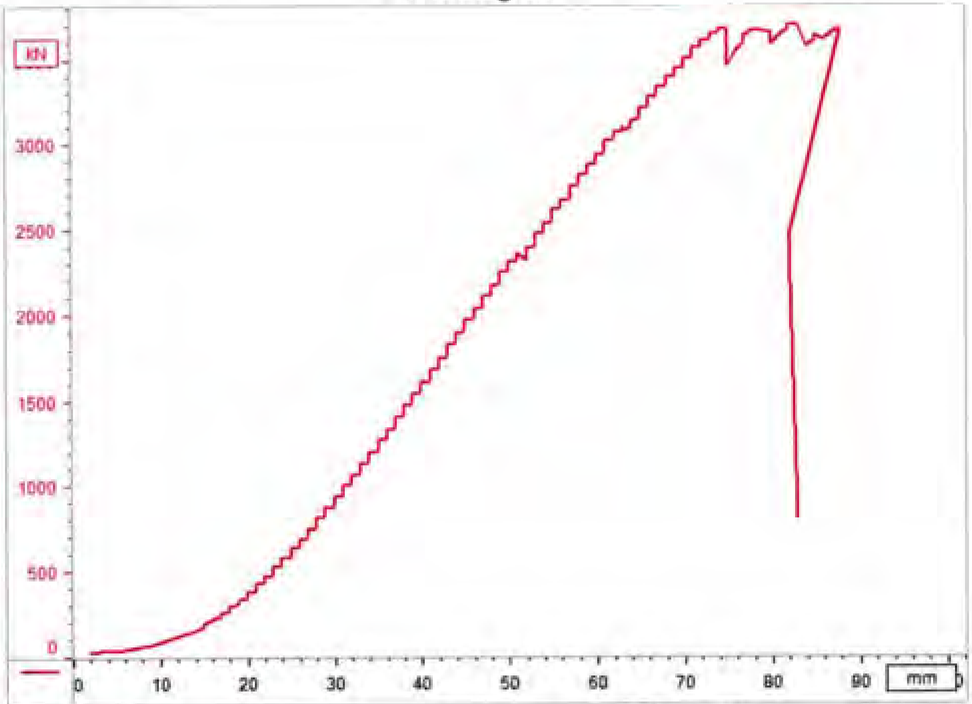
Part of AXLOAD

MENNENS

Klant / Customer	**TTI Testing**	Omschrijving / Description	
Order / Order	**748836**	**Breakload test steel wire rope 77mm**	
Object / Object	**Steel wire rope 77mm**		
		Opmerkingen / Remarks	
Serie nr. / Serial No.		**5M section bridle sample**	
Proeftype / Type of test	**Breekproef**		
Proef / Test	**0** van / of **0**	Starttijd /Time started	**24-11-2016 10:32:22**
Datum / Date	**24.11.2016**	Stoptijd /Time stopped	**24-11-2016 10:37:34**

Hoogste Kracht / Highest Force	**3707**	**kN**	Stijgtijd / Rising time **500**	kN/Min
Hoogste Rek/ Highest Elasticity	**92**	**mm**		

F-E Diagram



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Part of AxLoad

Appendix D – Calibration certificate for 250 kN tensile machine

CERTIFICATE OF CALIBRATION

ISSUED BY: ZWICK TESTING MACHINES LIMITED
UKAS ACCREDITED CALIBRATION LABORATORY
CERTIFICATE NUMBER: 1606-1209
DATE OF ISSUE: 16 June 2016

ilac-MRA

UKAS CALIBRATION
0167

Zwick / Roell

Page 1 of 3 Pages

Zwick Testing Machines Ltd
Southern Avenue, Leominster
Herefordshire HR6 0QH
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For Sales Call: +44 (0) 1568 615201 Fax: +44 (0) 1568 612626
Internet: www.zwick.co.uk

Approved Signatories
[redacted]

Issued To:	**TTI Testing Ltd**		
Address:	**Unit 2 Hithercroft Road, Wallingford, Oxfordshire OX10 9DG**		
Machine Description:	Servo Hydraulic Test Frame	**Serial Number:**	80184 000015
Manufacturer / Type / Year:	Dartec 250kN RE 1980	**Force Capacity:**	250kN
Display System:	Dell PC (7LM5582)	**Software:**	Cubus 2.0.125
Force Transducer:	Dartec Load Cell	**Serial Number:**	92039
Associated Equipment:	Cats3 Cube	**Serial Number:**	10226
Date of Calibration:	**09 June 2016**	**Ambient Temperature:**	**22.7°C**
Zwick reference numbers:	SA2005260.00, F104559		
Previous certificate number:	1511-2113	Issued on:	11 November 2015

Method:
The testing machine identified above has been calibrated in accordance with the requirements of **BS EN ISO 7500-1:2004** over the ranges given below for increasing forces only. The calibration was performed using force proving devices and / or masses which meet the requirements of BS EN ISO 7500-1 and equipment which is calibrated in accordance with BS EN ISO 376:2011.
The machine complied with the requirements of the standard for the following ranges and classifications with regard to the relative error, repeatability, resolution and zero return to which table 2 of the standard refers.

Range	Mode	Display	Status	Classification of range(s)
250kN	Tension	Display 1	As left	250kN Class 0.5 down to 2.5kN
250kN	Compression	Display 1	As left	250kN Class 0.5 down to 2.5kN

Detailed tabulated results are shown on the following pages.

Calibrated by: [redacted] **Certified by:** [redacted]

CERTIFICATE OF CALIBRATION

ISSUED BY: ZWICK TESTING MACHINES LIMITED
UKAS ACCREDITED CALIBRATION LABORATORY 0167
CERTIFICATE NUMBER: 1606-1209
DATE OF ISSUE: 16 June 2016

The following traceable force proving equipment was used for the calibration:

Description	Capacity	Class	Serial Number	Certificate Number	Date Calibrated
Load Cell	20kN	0.5	57334	5098	23 July 2014
Load Cell	250kN	0.5	52854	5185	15 September 2014

With reference to clause 6 of BS EN ISO 7500-1 the proving equipment used have been calibrated to BS EN ISO 376 and the class of the proving device(s) was equal to or exceeded the class to which the machine has been verified.

The expiry date of the certificates of calibration for the elastic proving devices used is 26 months and for masses 5 years from the dates given above.

Where masses are used, the value for gravity (g) used to calculate the forces exerted by the masses was $9.815m/s^2$

When using elastic proving devices the constant indicated force method was used to effect the verification. When masses are used the constant true force method was used to effect the verification. Three verification runs were made on each range

The Interval between verifications, clause 9 of the standards refers.

The time between verifications depends upon the type of testing machine, the standard of maintenance and the amount of use. Unless otherwise specified it is recommended that the verification be carried out at intervals not exceeding 12 months. The machine shall in any case be verified if it is moved to a new location necessitating dismantling or if it is subject to major repair or adjustment.

The Zwick Calibration Laboratory is accredited by UKAS to BS EN ISO 17025 (General requirements for the competence of testing and calibration laboratories) to perform the calibration which is reported on this certificate.

Prior to verification the machine was inspected for good working order and was found to satisfy the guidelines given in section 5 of BS EN ISO 7500-1

The calculation of the accuracy and repeatability errors and the classification of the testing machines performance was made in accordance with the method specified in Annex C of BS EN ISO 7500-1:2004

Where there are adjacent results at the same force increment, these are at the overlap point from the two proving devices used.

The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor k=2, providing a coverage probability of approximately 95%. The uncertainty evaluation has been carried out in accordance with UKAS requirements.
The uncertainty stated above refer to values obtained during calibration and make no allowances for factors such as long term drift, and alignment effects, the influences of these factors should be taken into account by the user.

CERTIFICATE OF CALIBRATION

ISSUED BY: ZWICK TESTING MACHINES LIMITED
UKAS ACCREDITED CALIBRATION LABORATORY 0167
CERTIFICATE NUMBER: 1606-1209
DATE OF ISSUE: 16 June 2016

Results:

Range 1 250kN Tension Display 1		Shunt Cal kN	Range 2 250kN Compression Display 1		Shunt Cal kN
These results are:	As left following adjustments		These results are:	As left following adjustments	
Nominal Force +ve	Relative Error	Relative Uncertainty	Nominal Force -ve	Relative Error	Relative Uncertainty
kN	%	%	kN	%	%
2.500	0.10	0.28	2.500	0.03	0.26
5.00	-0.04	0.28	5.00	0.12	0.27
12.50	-0.06	0.26	12.50	0.07	0.26
12.50	-0.18	0.26	12.50	0.12	0.29
25.00	-0.11	0.24	25.00	0.06	0.24
50.00	-0.04	0.24	50.00	0.04	0.24
100.00	0.03	0.24	100.00	0.01	0.24
150.00	0.11	0.24	150.00	-0.03	0.24
200.00	0.17	0.24	200.00	-0.04	0.24
250.00	0.24	0.24	250.00	-0.13	0.24

In the result table(s) above a negative relative error indicates that the machine indicator lags the true applied force.

The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor k=2, providing a coverage probability of approximately 95%. The uncertainty evaluation has been carried out in accordance with UKAS requirements.
The uncertainty stated above refer to values obtained during calibration and make no allowances for factors such as long term drift, and alignment effects, the influences of these factors should be taken into account by the user.

Appendix E - Results of the mechanical testing on rope wires

This appendix presents the results of the mechanical tests on the wires taken from the drum, tug side and bridle samples. Where appropriate, wires were taken from different strands (numbered arbitrarily as described in Section 12 above). Table E1 below summarises the designation used in the results Tables to identify wires from the different positions in the wire rope construction.

Description of wire position in rope	Wire designation in results Tables
Outer Strand (#) Outer Wire (#)	OS# OW#
Outer Strand (#) 2nd Layer Large	OS# 2LL
Outer Strand (#) 2nd Layer Small	OS# 2LS
Outer Strand (#) 3rd Layer	OS# 3L
Outer Strand (#) Core Wire	OS# CW
IWRC Outer Strand, Outer Wire	IWRC OS OW
IWRC Outer Strand, Core Wire	IWRC OS CW
IWRC Core Strand, Outer Wire	IWRC CS OW
IWRC Core Strand, Core Wire	IWRC CS CW

Table E1: Description and short designation of the wire samples used in the results Tables.

In each case, the results of the tests on the wires have been compared to the original measured value on the wire stock (where known) or in the absence of this information to the minimum requirement specified by the appropriate standard. In order to aid a 'quick' interpretation of the results, on the right hand side of each table is a column with coloured cells. These cells are coloured as follows:

- green where the test result met or exceeded the original (or standard minimum) value,
- orange if they were at or above 90% but below 100%; and,
- red if below 90%.

Designation	Nom. Diameter / Measured Diameter	Original grade / Nominal grade	Measured BL	Clear of Grip	Grade based on Nom. Dia and measured BL	% Original nominal grade	
	(mm)	(N/mm^2)	(kN)	(Y / N)	(N/mm^2)	(%)	
OS1 OW1	4.39	2164	34.403	Y	2273	105	
OS1 OW2	4.39	2164	33.047	Y	2183	101	
OS1 OW3	4.39	2164	32.587	Y	2153	99	
OS2 OW1	4.39	2164	33.588	N	2219	103	
OS2 OW2	4.39	2164	33.903	Y	2240	104	
OS2 OW3	4.39	2164	34.496	Y	2279	105	
OS3 OW1	4.39	2164	33.077	Y	2185	101	
OS3 OW2	4.39	2164	33.651	N	2223	103	
OS3 OW3	4.39	2164	34.063	Y	2250	104	
OS4 OW1	4.39	2164	34.157	Y	2257	104	
OS4 OW2	4.39	2164	33.722	Y	2228	103	
OS4 OW3	4.39	2164	34.315	Y	2267	105	
OS1 2LL	3.53	2128	21.737	Y	2221	104	
OS2 2LL	3.53	2128	21.499	Y	2197	103	
OS3 2LL	3.53	2128	21.681	Y	2215	104	
OS1 2LS	2.73	2096	13.254	Y	2264	108	
OS2 2LS	2.73	2096	13.068	N	2233	107	
OS3 2LS	2.73	2096	13.355	Y	2282	109	
OS1 3L	3.62	2075	22.024	Y	2140	103	
OS2 3L	3.62	2075	22.342	Y	2171	105	
OS3 3L	3.62	2075	22.743	Y	2210	106	
OS1 CW	4.81	2087	39.330	Y	2164	104	
IWRC OS OW	3.14	2060	17.375	Y	2251	109	
IWRC OS CW	3.38	2060	19.495	Y	2173	105	
IWRC CS OW	3.61	2060	21.539	Y	2104	102	
IWRC CS CW	3.99	2060	26.284	Y	2107	102	

Table E2: Results of the tensile tests on wires taken from the drum sample.

Designation	Nom. Diameter	Nominal grade	No. of turns to failure	Clear of Grip	No. of turns to failure	Usha Martin test cert (for wires)	API 9A level 5 / level 4	
	(mm)	(N/mm^2)	(-)	(Y / N)	(/100d_w)	(-)	(-)	
OS1 OW1	4.39	2164	5	Y (2)	7	13	10	
OS1 OW2	4.39	2164	1	Y (2)	1	13	10	
OS1 OW3	4.39	2164	23	Y (4)	34	13	10	
OS2 OW1	4.39	2164	24	N (2)	35	13	10	
OS2 OW2	4.39	2164	18	Y (2)	26	13	10	
OS2 OW3	4.39	2164	2	Y (2)	3	13	10	
OS3 OW1	4.39	2164	22	N (2)	32	13	10	
OS3 OW2	4.39	2164	4	Y (2)	6	13	10	
OS3 OW3	4.39	2164	6	Y (2)	9	13	10	
OS4 OW1	4.39	2164	20	N (3)	29	13	10	
OS4 OW2	4.39	2164	12	Y (2)	18	13	10	
OS4 OW3	4.39	2164	5	Y (2)	7	13	10	
OS1 2LL	3.53	2128	30	Y (4)	35	17	12	
OS2 2LL	3.53	2128	29	Y (4)	34	17	12	
OS3 2LL	3.53	2128	30	Y (4)	35	17	12	
OS1 2LS	2.73	2096	33	Y (3)	30	23	19	
OS2 2LS	2.73	2096	31	N (3)	28	23	19	
OS3 2LS	2.73	2096	27	Y (2)	25	23	19	
OS1 3L	3.62	2075	9	Y (2)	11	16	14	
OS2 3L	3.62	2075	24	Y (3)	29	16	14	
OS3 3L	3.62	2075	24	Y (4)	29	16	14	
OS1 CW	4.81	2087	17	Y (3)	27	12	10	
IWRC OS OW	3.14	2060	7	Y (2)	7		16	
IWRC OS CW	3.38	2060	12	Y (2)	14		15	
IWRC CS OW	3.61	2060	9	Y (2)	11		14	
IWRC CS CW	3.99	2060	23	Y (2)	31		13	

Table E3: Results of the torsion tests on wires taken from the drum sample.

Designation	Nom. Diameter	Bend Radius	No. of bends to failure	ISO 10264-2 2012	% ISO 10264-2 2012	
	(mm)	(mm)	(-)	(-)	(%)	
OS1 OW1	4.39	15	13	7	186	
OS1 OW2	4.39	15	10	7	143	
OS1 OW3	4.39	15	11	7	157	
OS2 OW1	4.39	15	11	7	157	
OS2 OW2	4.39	15	16	7	229	
OS2 OW3	4.39	15	13	7	186	
OS3 OW1	4.39	15	12	7	171	
OS3 OW2	4.39	15	11	7	157	
OS3 OW3	4.39	15	12	7	171	
OS4 OW1	4.39	15	12	7	171	
OS4 OW2	4.39	15	11	7	157	
OS4 OW3	4.39	15	8	7	114	
OS1 2LL	3.53	10	10	5	200	
OS2 2LL	3.53	10	10	5	200	
OS3 2LL	3.53	10	11	5	220	
OS1 2LS	2.73	7.5	11	6	183	
OS2 2LS	2.73	7.5	11	6	183	
OS3 2LS	2.73	7.5	10	6	167	
OS1 3L	3.62	10	10	5	200	
OS2 3L	3.62	10	9	5	180	
OS3 3L	3.62	10	11	5	220	
OS1 CW	4.81	15	13	5	260	
IWRC OS OW	3.14	10	12	11	109	
IWRC OS CW	3.38	10	12	9	133	
IWRC CS OW	3.61	10	10	6	167	
IWRC CS CW	3.99	10	-	4	-	

Table E4: Results of the reverse bend tests on wires taken from the drum sample.

Designation	Nom. Diameter / Measured Diameter	Original grade / Nominal grade	Measured BL	Clear of Grip	Grade based on Nom. Dia and measured BL	% Original nominal grade	
	(mm)	(N/mm^2)	(kN)	(Y / N)	(N/mm^2)	(%)	
OS1 OW1	4.39	2164	30.509	Y	2016	93	
OS1 OW2	4.39	2164	30.215	Y	1996	92	
OS1 OW3	4.39	2164	31.178	Y	2060	95	
OS2 OW1	4.39	2164	30.411	Y	2009	93	
OS2 OW2	4.39	2164	31.979	Y	2113	98	
OS2 OW3	4.39	2164	29.980	Y	1981	92	
OS3 OW1	4.39	2164	31.433	Y	2077	96	
OS3 OW2	4.39	2164	32.386	Y	2140	99	
OS3 OW3	4.39	2164	31.193	Y	2061	95	
OS4 OW1	4.39	2164	30.663	Y	2026	94	
OS4 OW2	4.39	2164	30.234	Y	1997	92	
OS4 OW3	4.39	2164	27.159	Y	1794	83	
OS1 2LL	3.53	2128	21.426	Y	2189	103	
OS2 2LL	3.53	2128	21.083	Y	2154	101	
OS3 2LL	3.53	2128	22.139	Y	2262	106	
OS1 2LS	2.73	2096	13.334	Y	2278	109	
OS2 2LS	2.73	2096	12.933	N	2209	105	
OS3 2LS	2.73	2096	13.021	N	2224	106	
OS1 3L	3.62	2075	22.448	Y	2181	105	
OS2 3L	3.62	2075	21.287	Y	2068	100	
OS3 3L	3.62	2075	21.273	Y	2067	100	
OS1 CW	4.81	2087	39.376	N	2167	104	
IWRC OS OW	3.14	2060	16.339	Y	2117	103	
IWRC OS CW	3.38	2060	19.256	Y	2146	104	
IWRC CS OW	3.61	2060	20.363	Y	1989	97	
IWRC CS CW	3.99	2060	25.115	Y	2014	98	

Table E5: Results of the tensile tests on wires taken from the tug side sample.

Designation	Nom. Diameter	Nominal grade	No. of turns to failure	Clear of Grip	No. of turns to failure	Usha Martin test cert (for wires)	API 9A level 5 / level 4	
	(mm)	(N/mm^2)	(-)	(Y / N)	($/100d_w$)	(-)	(-)	
OS1 OW1	4.39	2164	2	Y (2)	3	13	10	
OS1 OW2	4.39	2164	1	Y (2)	1	13	10	
OS1 OW3	4.39	2164	2	Y (2)	3	13	10	
OS2 OW1	4.39	2164	1	Y (2)	1	13	10	
OS2 OW2	4.39	2164	2	Y (2)	3	13	10	
OS2 OW3	4.39	2164	1	Y (2)	1	13	10	
OS3 OW1	4.39	2164	1	Y (2)	1	13	10	
OS3 OW2	4.39	2164	2	Y (2)	3	13	10	
OS3 OW3	4.39	2164	2	Y (2)	3	13	10	
OS4 OW1	4.39	2164	3	Y (2)	4	13	10	
OS4 OW2	4.39	2164	4	Y (2)	6	13	10	
OS4 OW3	4.39	2164	1	Y (2)	1	13	10	
OS1 2LL	3.53	2128	28	Y (4)	33	17	12	
OS2 2LL	3.53	2128	27	N (3)	32	17	12	
OS3 2LL	3.53	2128	23	Y (3)	27	17	12	
OS1 2LS	2.73	2096	30	N (3)	27	23	19	
OS2 2LS	2.73	2096	22	Y (2)	20	23	19	
OS3 2LS	2.73	2096	22	Y (2)	20	23	19	
OS1 3L	3.62	2075	25	Y (4)	30	16	14	
OS2 3L	3.62	2075	27	N (3)	33	16	14	
OS3 3L	3.62	2075	23	Y (3)	28	16	14	
OS1 CW	4.81	2087	17	Y (2)	27	12	10	
IWRC OS OW	3.14	2060	1	Y (2)	1		16	
IWRC OS CW	3.38	2060	7	Y (2)	8		15	
IWRC CS OW	3.61	2060	-	-			14	
IWRC CS CW	3.99	2060	-	-			13	

Table E6: Results of the torsion tests on wires taken from the tug side sample.

Designation	Nom. Diameter	Bend Radius	No. of bends to failure	ISO 10264-2 2012	% ISO 10264-2 2012	
	(mm)	(mm)	(-)	(-)	(%)	
OS1 OW1	4.39	15	6	7	86	
OS1 OW2	4.39	15	7	7	100	
OS1 OW3	4.39	15	6	7	86	
OS2 OW1	4.39	15	7	7	100	
OS2 OW2	4.39	15	10	7	143	
OS2 OW3	4.39	15	8	7	114	
OS3 OW1	4.39	15	8	7	114	
OS3 OW2	4.39	15	9	7	129	
OS3 OW3	4.39	15	7	7	100	
OS4 OW1	4.39	15	5	7	71	
OS4 OW2	4.39	15	5	7	71	
OS4 OW3	4.39	15	5	7	71	
OS1 2LL	3.53	10	11	5	220	
OS2 2LL	3.53	10	10	5	200	
OS3 2LL	3.53	10	9	5	180	
OS1 2LS	2.73	7.5	10	6	167	
OS2 2LS	2.73	7.5	10	6	167	
OS3 2LS	2.73	7.5	10	6	167	
OS1 3L	3.62	10	11	5	220	
OS2 3L	3.62	10	10	5	200	
OS3 3L	3.62	10	9	5	180	
OS1 CW	4.81	15	11	5	220	
IWRC OS OW	3.14	10	8	11	73	
IWRC OS CW	3.38	10	7	9	78	
IWRC CS OW	3.61	10	6	6	100	
IWRC CS CW	3.99	10	8	4	200	

Table E7: Results of the reverse bend tests on wires taken from the tug side sample.

Designation	Nom. Diameter / Measured Diameter	Original grade / Nominal grade	Measured BL	Clear of Grip	Grade based on Nom. Dia and measured BL	% Original nominal grade	
	(mm)	(N/mm^2)	(kN)	(Y / N)	(N/mm^2)	(%)	
OS1 OW1	4.39	2164	28.985	Y	1915	88	
OS1 OW2	4.39	2164	29.551	Y	1952	90	
OS1 OW3	4.39	2164	29.496	Y	1949	90	
OS2 OW1	4.39	2164	27.842	Y	1839	85	
OS2 OW2	4.39	2164	25.586	Y	1690	78	
OS2 OW3	4.39	2164	28.007	Y	1850	86	
OS3 OW1	4.39	2164	25.093	Y	1658	77	
OS3 OW2	4.39	2164	26.314	Y	1738	80	
OS3 OW3	4.39	2164	28.542	Y	1886	87	
OS4 OW1	4.39	2164	28.221	Y	1864	86	
OS4 OW2	4.39	2164	28.115	Y	1857	86	
OS4 OW3	4.39	2164	23.930	Y	1581	73	
OS1 2LL	3.53	2128	22.297	Y	2278	107	
OS2 2LL	3.53	2128	21.063	Y	2152	101	
OS3 2LL	3.53	2128	21.373	Y	2184	103	
OS1 2LS	2.73	2096	12.921	Y	2207	105	
OS2 2LS	2.73	2096	12.842	Y	2194	105	
OS3 2LS	2.73	2096	13.228	Y	2260	108	
OS1 3L	3.62	2075	22.648	N	2201	106	
OS2 3L	3.62	2075	22.381	N	2175	105	
OS3 3L	3.62	2075	22.800	N	2215	107	
OS1 CW	4.81	2087	36.347	Y	2000	96	
IWRC OS OW	3.14	2060	15.873	N	2056	100	
IWRC OS CW	3.38	2060	19.164	Y	2136	104	
IWRC CS OW	3.61	2060	21.273	N	2078	101	
IWRC CS CW	3.99	2060	26.076	N	2091	101	

Table E8: Results of the tensile tests on wires taken from the bridle sample.

Designation	Nom. Diameter	Nominal grade	No. of turns to failure	Clear of Grip	No. of turns to failure	Usha Martin test cert (for wires)	API 9A level 5 / level 4	
	(mm)	(N/mm^2)	(-)	(Y / N)	($/100d_w$)	(-)	(-)	
OS1 OW1	4.39	2164	1	Y (2)	1	13	10	
OS1 OW2	4.39	2164	1	Y (2)	1	13	10	
OS1 OW3	4.39	2164	2	Y (2)	3	13	10	
OS2 OW1	4.39	2164	4	Y (2)	6	13	10	
OS2 OW2	4.39	2164	5	Y (2)	7	13	10	
OS2 OW3	4.39	2164	1	Y (2)	1	13	10	
OS3 OW1	4.39	2164	1	Y (2)	1	13	10	
OS3 OW2	4.39	2164	2	Y (2)	3	13	10	
OS3 OW3	4.39	2164	2	Y (2)	3	13	10	
OS4 OW1	4.39	2164	1	Y (2)	1	13	10	
OS4 OW2	4.39	2164	12	N (2)	18	13	10	
OS4 OW3	4.39	2164	2	Y (2)	3	13	10	
OS1 2LL	3.53	2128	25	Y (4)	29	17	12	
OS2 2LL	3.53	2128	25	Y (3)	29	17	12	
OS3 2LL	3.53	2128	20	N (3)	24	17	12	
OS1 2LS	2.73	2096	30	Y (3)	27	23	19	
OS2 2LS	2.73	2096	31	Y (3)	28	23	19	
OS3 2LS	2.73	2096	33	Y (4)	30	23	19	
OS1 3L	3.62	2075	13	N (2)	16	16	14	
OS2 3L	3.62	2075	23	Y (3)	28	16	14	
OS3 3L	3.62	2075	24	Y (3)	29	16	14	
OS1 CW	4.81	2087	19	Y (3)	30	12	10	
IWRC OS OW	3.14	2060	1	Y (2)	1		16	
IWRC OS CW	3.38	2060	8	Y (2)	9		15	
IWRC CS OW	3.61	2060	-	-	-		14	
IWRC CS CW	3.99	2060	-	-	-		13	

Table E9: Results of the torsion tests on wires taken from the bridle sample.

Designation	Nom. Diameter	Bend Radius	No. of bends to failure	ISO 10264-2 2012	% ISO 10264-2 2012
	(mm)	(mm)	(-)	(-)	(%)
OS1 OW1	4.39	15	7	7	100
OS1 OW2	4.39	15	6	7	86
OS1 OW3	4.39	15	7	7	100
OS2 OW1	4.39	15	6	7	86
OS2 OW2	4.39	15	9	7	129
OS2 OW3	4.39	15	5	7	71
OS3 OW1	4.39	15	8	7	114
OS3 OW2	4.39	15	5	7	71
OS3 OW3	4.39	15	8	7	114
OS4 OW1	4.39	15	8	7	114
OS4 OW2	4.39	15	6	7	86
OS4 OW3	4.39	15	3	7	43
OS1 2LL	3.53	10	10	5	200
OS2 2LL	3.53	10	9	5	180
OS3 2LL	3.53	10	9	5	180
OS1 2LS	2.73	7.5	9	6	150
OS2 2LS	2.73	7.5	8	6	133
OS3 2LS	2.73	7.5	9	6	150
OS1 3L	3.62	10	9	5	180
OS2 3L	3.62	10	9	5	180
OS3 3L	3.62	10	9	5	180
OS1 CW	4.81	15	11	5	220
IWRC OS OW	3.14	10	5	11	45
IWRC OS CW	3.38	10	10	9	111
IWRC CS OW	3.61	10	6	6	100
IWRC CS CW	3.99	10	7	4	175

Table E10: Results of the reverse bend tests on wires taken from the bridle sample.

Appendix F - Results of the average zinc coat weight measurement

wire code	nominal diameter	mass before	mass after	Loss	coating weight	initial typ.	Class B	% Class B	
-	(mm)	(g)	(g)	g	(g/m^2)	(g/m^2)	(g/m^2)	(%)	
OS1 OW1	4.39	12.1601	11.9125	0.2476	179	161	150	119.3	
OS1 OW2	4.39	11.6972	11.4912	0.2060	154	161	150	102.9	
OS1 OW3	4.39	11.7503	11.5057	0.2446	183	161	150	122.1	
OS1 OW4	4.39	11.7583	11.5074	0.2509	188	161	150	125.2	
OS1 OW5	4.39	12.2736	12.0311	0.2425	174	161	150	115.7	
OS1 OW6	4.39	12.3120	12.0936	0.2184	156	161	150	103.7	
OS1 OW7	4.39	11.6690	11.4809	0.1881	141	161	150	94.1	
OS1 OW8	4.39	11.9468	11.7197	0.2271	167	161	150	111.3	
OS1 OW9	4.39	12.1663	11.9535	0.2128	153	161	150	102.2	
OS1 OW10	4.39	11.6723	11.4693	0.2030	152	161	150	101.6	
OS1 OW11	4.39	11.8522	11.6434	0.2088	154	161	150	103.0	
OS1 OW12	4.39	11.9202	11.6969	0.2233	164	161	150	109.6	
OS1 OW13	4.39	12.0869	11.8858	0.2011	146	161	150	97.2	
OS1 OW14	4.39	12.1835	11.9527	0.2308	166	161	150	110.9	
OS1 2LL1	3.53	7.3512	7.2030	0.1482	142	146	135	105.6	
OS1 2LL2	3.53	7.3960	7.2180	0.1780	171	146	135	126.5	
OS1 2LS1	2.73	4.4695	4.3902	0.0793	97	142	135	71.7	
OS1 2LS2	2.73	4.4018	4.3184	0.0834	103	142	135	76.6	
OS1 3L	3.62	7.7052	7.5403	0.1649	155	145	135	115.1	
OS1 CW	4.81	13.7557	13.5083	0.2474	173	163	150	115.2	
IWRC OS OW	3.14	7.2617	7.1162	0.1455	126	-	135	93.2	
IWRC OS CW	3.38	8.0599	7.8256	0.2343	199	-	135	147.1	
IWRC CS OW	3.61	9.8817	9.6516	0.2301	169	-	135	125.1	
IWRC CS CW	3.99	11.6130	11.3448	0.2682	185	-	135	136.9	

Table F1: Measurement of average residual galvanising levels on the drum sample wires.

wire code	nominal diameter	mass before	mass after	Loss	coating weight	inital typ.	Class B	% Class B	
-	(mm)	(g)	(g)	g	(g/m^2)	(g/m^2)	(g/m^2)	(%)	
OS1 OW1	4.39	11.6655	11.5611	0.1044	78	161	150	51.9	
OS1 OW2	4.39	11.2362	11.1515	0.0847	65	161	150	43.6	
OS1 OW3	4.39	11.9618	11.8631	0.0987	72	161	150	47.8	
OS1 OW4	4.39	11.3914	11.2984	0.0930	71	161	150	47.3	
OS1 OW5	4.39	10.9835	10.9147	0.0688	54	161	150	36.2	
OS1 OW6	4.39	11.0161	10.9406	0.0755	59	161	150	39.6	
OS1 OW7	4.39	12.0745	11.9700	0.1045	75	161	150	50.1	
OS1 OW8	4.39	11.9855	11.8893	0.0962	70	161	150	46.5	
OS1 OW9	4.39	11.0491	10.9528	0.0963	76	161	150	50.5	
OS1 OW10	4.39	11.8069	11.7017	0.1052	77	161	150	51.6	
OS1 OW11	4.39	11.5376	11.4558	0.0818	62	161	150	41.0	
OS1 OW12	4.39	11.1856	11.1007	0.0849	66	161	150	43.9	
OS1 OW13	4.39	11.4109	11.3290	0.0819	62	161	150	41.5	
OS1 OW14	4.39	11.6069	11.4868	0.1201	90	161	150	60.0	
OS1 2LL1	3.53	7.6788	7.5572	0.1216	111	146	135	82.5	
OS1 2LL2	3.53	7.5198	7.3347	0.1851	175	146	135	129.5	
OS1 2LS1	2.73	4.5061	4.4117	0.0944	115	142	135	84.9	
OS1 2LS2	2.73	4.4481	4.3924	0.0557	68	142	135	50.3	
OS1 3L	3.62	7.6196	7.4406	0.1790	171	145	135	126.6	
OS1 CW	4.81	13.7464	13.4423	0.3041	213	163	150	142.3	
IWRC OS OW	3.14	6.9071	6.8615	0.0456	41	-	135	30.3	
IWRC OS CW	3.38	7.9889	7.9263	0.0626	52	-	135	38.8	
IWRC CS OW	3.61	8.2384	8.1692	0.0692	60	-	135	44.4	
IWRC CS CW	3.99	9.7716	9.659	0.1126	91	-	135	67.5	

Table F2: Measurement of average residual galvanising levels on the tug side sample wires.

wire code	nominal diameter	mass before	mass after	Loss	coating weight	initial typ.	Class B	% Class B	
-	(mm)	(g)	(g)	g	(g/m^2)	(g/m^2)	(g/m^2)	(%)	
OS1 OW1	4.39	10.9250	10.8209	0.1041	83	161	150	55.2	
OS1 OW2	4.39	11.6062	11.5090	0.0972	73	161	150	48.5	
OS1 OW3	4.39	11.6230	11.5087	0.1143	86	161	150	57.0	
OS1 OW4	4.39	11.9404	11.8410	0.0994	72	161	150	48.2	
OS1 OW5	4.39	11.3663	11.2622	0.1041	80	161	150	53.1	
OS1 OW6	4.39	11.9399	11.8252	0.1147	84	161	150	55.7	
OS1 OW7	4.39	11.3542	11.2496	0.1046	80	161	150	53.4	
OS1 OW8	4.39	11.8231	11.7065	0.1166	86	161	150	57.2	
OS1 OW9	4.39	11.0834	10.9737	0.1097	86	161	150	57.4	
OS1 OW10	4.39	11.0463	10.9424	0.1039	82	161	150	54.5	
OS1 OW11	4.39	11.2141	11.1131	0.1010	78	161	150	52.2	
OS1 OW12	4.39	10.9601	10.8587	0.1014	80	161	150	53.6	
OS1 OW13	4.39	11.9381	11.8219	0.1162	85	161	150	56.4	
OS1 OW14	4.39	10.9234	10.8348	0.0886	70	161	150	47.0	
OS1 2LL1	3.53	7.1762	7.0288	0.1474	145	146	135	107.6	
OS1 2LL2	3.53	7.3485	7.1865	0.1620	156	146	135	115.6	
OS1 2LS1	2.73	4.2650	4.2016	0.0634	81	142	135	59.9	
OS1 2LS2	2.73	4.3790	4.2950	0.0840	105	142	135	77.6	
OS1 3L	3.62	7.6649	7.5249	0.1400	132	145	135	97.9	
OS1 CW	4.81	13.5261	13.2647	0.2614	186	163	150	124.0	
IWRC OS OW	3.14	6.4250	6.3841	0.0409	39	-	135	29.2	
IWRC OS CW	3.38	6.9820	6.9421	0.0399	38	-	135	28.2	
IWRC CS OW	3.61	9.2116	9.1228	0.0888	69	-	135	51.1	
IWRC CS CW	3.99	10.8603	10.7649	0.0954	69	-	135	51.3	

Table F3: Measurement of average residual galvanising levels on the bridle sample wires.