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Experimental investigation of corrosion effect on bending fatigue of the wire ropes

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Wire rope has examined for the total fatigue life prediction methodologies based on the initial condition of the wire rope. The great majority of applications, e.g. cranes, lifts, and winches have been subjected the rope to bending fatigue. There are several parameters which effects on bending fatigue lifetime such as tensile load, sheave diameter, rope composition. Apart from that, according to application area, wire ropes have often exposed to atmospheric influences, and corrosion become inevitable. In this study, in order to determine the exact lifetime of wire rope, corrosion, as a major degradation influence has been investigated experimentally. Bending fatigue tests have been performed for pre-corroded wire ropes with different level of corrosion, and the data have been compared with the reference test results. For comparison of the combine effect of corrosion with tensile loads, and corrosion with sheave diameters, two different tensile loads and sheave diameters have been tested. In this paper, it has been reported the outcome of a series of test undertaken on 6 x 36 Warrington-Seale ropes in order to determine their exact fatigue endurance under different conditions.

Keywords: Wire ropes, Fatigue, Corrosion

1 Introduction

Steel wire rope is a critical component in many engineering applications, such as including cranes, mine hoisting, offshore mooring systems. Although there are many different constructions of rope available with a range of characteristics to suit the variety of applications, a wire rope consists of a large number of wires spun or twisted together to create complex structures, sharing many parallel load paths, which combine high axial strength and stiffness with flexibility in bending. The simplest geometry of rope will consist of layers of concentric wires around a central wire (termed a spiral strand). More complicated stranded ropes have a double helix arrangement where helically spun strands (usually six or eight) are themselves spun around a core, which is a rope in itself.

The great majority of applications, will subject the rope to bending fatigue. Fatigue loading may be split into two categories; a mean tensile load with a superimposed fluctuating tensile load which name is tension-tension fatigue and a static tensile load combined with repeated bending which name is bending over sheave or bending fatigue. Experimental studies have been performed to investigate how steel wire rope samples are affected by corrosion.

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In the literature, several investigations by many authors have been performed in order to determine effect of axial fatigue or BoS fatigue to the lifetime of the steel wire ropes[1-11]. Feyrer[1] has presented the results of experimental test results of steel wire ropes subjected to BoS fatigue. He investigated effects of various parameters (tensile load, sheave diameter, zinc coating, sheave geometry and material, side deflection, winding angle) on the rope`s BoS fatigue lifetime. Elata *et al.*[2] presented a new model of wire rope which is subjected to axial load and axial torque and validated their model experimentally. Onur and Imrak[3] investigated effects of the tensile load (S) and diameter of sheave (D) to the BoS fatigue endurance of wire ropes. Torkar and Arzensek[4] conducted bending fatigue tests of wires located in outer strands of 6 x 19 seale rope. Giglio and Manes[5] examined the effect of winding angle parameter between rope and sheave to the bending fatigue life of 19 x 7 non-rotating rope which may be used in aircraft rescue hoist, that has nineteen strands and each strand has seven wires. They concluded that ropes had more flexibility and superior endurance limit when ropes having more external wires and external strands were used. In addition lang lay ropes had longer lifetime than regular lay ropes when fiber core was used. Garbatov *et al.*[6] studied the effects of some parameters (wire rope core type, type of lubricant, tensile load) on bending fatigue lifetime of 6 x 36 Warrington-

Seale rope with 16 mm diameter. Urchegui *et al.*[7] investigated wear evolution in a 6 x 19 Seale stranded rope subjected to bending fatigue. Ridge *et al.*[8] examined the effects of degradation (wire breaks, abrasive wear, slack wires, slack strands, plastic wear, corrosion, torsional imbalance) to the BoS fatigue endurance of steel wire ropes. Onur and Imrak[9] investigated the effect of internal and external wire breaks, abrasive wear, in sufficient lubrication, curling on bending over sheave fatigue life of 6 x 36 Warrington Seale wire ropes.Schönherr[10] studied the effect of fleet angle of steel wire ropes subjected to BoS fatigue. Ridge *et al.* [11] identified the strain and its distribution of steel wire rope subjected to bending fatigue by sticking strain gage on various place on each wires.

Experimental studies on wire rope fatigue have been classified in two main categories: tension-tension fatigue, bending over sheave. Mainly investigated parameters are tensile load (S), sheave diameter effect (D/d ratio), fleet angle, insufficient lubrication, wear, and broken wire. However wire ropes are usually exposed to atmospheric affect that causes corrosion. In this study corrosion effect of wire rope which is inevitable under this circumstance are examined experimentally. Besides corrosion fatigue behavior is examined for various type of conventional materials sample.

Gruenberg *et al.*[12] investigated fatigue life of pre-corroded 2024-T3 aluminium. They used fatigue specimens of aluminium alloy 2024-T3 that were exposed to corrosion and tested in laboratory setting. The test samples were taken from a single lot of material and corroded6, 24, and72 hours in three specimen orientations. The corroded specimens were cycled to failure at three stress levels. Chamos *et al.*[13] investigated constant amplitude fatigue tests have been performed using smooth specimens of a rolled AZ31 magnesium alloy in order to assess the fatigue behavior of the material. They investigated the fatigue limit is reduced to 50% of the respective value of the un-corroded material. Obert *et al.*[14] examined in aging aircraft, the synergetic interaction between corrosion and fatigue. It has been shown to reduce the life expectancy of aluminium alloys. The fatigue life of the specimens decreased in an inverse exponential fashion as mass loss per unit area increased. The hardness values of the corroded surfaces were also observed to drop. Burns *et al.*[15] investigated the effect of existing-localized corrosion on fatigue cracking of 7075-T6511 was established using crack surface marker-band analysis and a fracture mechanics model. The effect of pre-corrosion exposure time, solution, and localized corrosion morphology on fatigue cracking of peak aged Al–Zn–Cu–Mg was measured and modeled using crack surface microscopic analysis and a fracture mechanics tool. Jones and Hoeppner[16] investigated pit-to-crack transition experimentally. 1.600 mm and 4.064 mm 7075-T6 aluminium alloy specimen were corroded using a 15:1 ratio of 3.5% NaCl solution and H_2O_2 prior to fatigue loading. Cracks originating from corrosion pits were visually investigated in order to understand how pit-to-crack transitions occur. Begum *et al.*[17]examined corrosion fatigue behavior of four types of austenitic stainless steels were investigated in boiling 45% magnesium chloride solution at a stress ratio of 0.25 and a frequency of 0.1 Hz. Type 316LN stainless steel possessed the best resistance and type 304 stainless steel had the lowest resistance to corrosion fatigue.

Various researchers have studied the mechanisms of corrosion in terms of microstructural and environmental influences[12-17]. However it has not applied to real wire rope structure. In this study fatigue experiment was conducted to pre-corroded wire rope sample, in order to examine synergistic effect corrosion and fatigue.

2 Experimental Investigation

To investigate the corrosion effect, steel wire ropes with 10 mm in diameter have been selected for many practical reasons.6 x 36 Warrington-seale (WS) rope construction with Independent Wire Rope Core IWRC can be seen in Fig. 1.Warrington-Seale rope construction offers optimum resistance in fatigue and crushing. Mechanical properties of this rope were given in Table 1.

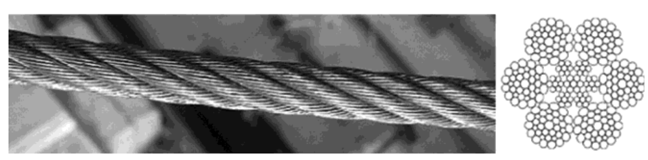


Fig. 1 — 6 x36 Warrington-Seale wire rope sample and its cross sectional view.

Table 1 — Technical properties of 6 x 36 Warrington-Seale wire rope

Number of Strand	6
Construction	6 x (1+7+(7+7)+14)
Diameter	10 mm
Wire grade	1960 N/mm^2
Lay Type	Right regular lay (sZ)
Minimum breaking load	71,6 kN

For the corrosion test set up, the accelerated salt spray fog environment has been used. The tests were conducted according to ASTM B117 specification. The corrosive solution was prepared by dissolving 5 parts by mass of sodium chloride in 95 parts of water. In the middle of wire ropes which are enforced bending over sheave exposed to corrosion effect. To comparison, all experiments were carried out also for the non-corroded material.

The corrosion test setup has been created with a metal box above the oven and sand used for distributing the heat all over the box homogeneously as shown in Fig. 2. Corrosion of samples was accomplished by the utilization of a corrosion cell. The solution composition for the corrosion bath 5% wt. of NaCl and 95% wt. of H_2O to simulate the aggressive environment.

This batch procedure was used to expose each of the three levels of corrosion, consequently ensuring that all the samples for a given level of corrosion were exposed to the same corrosive environment. Figure 3 shows the corrosion level of wire ropes. Since each of the corrosion solutions was mixed using identical amounts of measured reagents and identical mixing procedures, it can be assumed that the three different batches of corrosion exposures started with essentially the same initial solution.

In order to assess the effect of prior corrosion damage on the fatigue behavior of the alloy under

Fig. 2 — Building stage of corrosion cell.

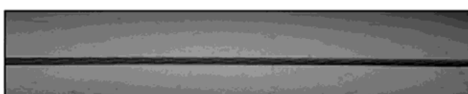
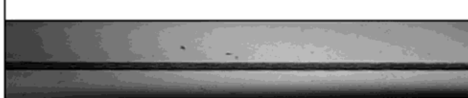
	6x36 Warrington Seale rope sample without corrosion.
	6x36 Warrington Seale rope sample, has been kept in salt water solution for one week.
	6x36 Warrington Seale rope sample has been kept in salt water solution for two weeks.
	6x36 Warrington Seale rope sample has been kept in salt water solution for three weeks.

Fig. 3 — Pre-corroded 6x36 Warrington seale wire rope with three level.

investigation a number of specimens have been exposed to corrosion environment prior to fatigue testing. Prior to corrosion exposure, the surface of the specimens were not cleaned in order to remove any oily lubricant. For the corrosion tests, the accelerated salt spray fog environment has been used.

To investigate effect of corrosion to the service life of steel ropes running with sheaves various tests have been conducted in the rope technology laboratory of Institute of Mechanical Handling and Logistics University of Stuttgart, Germany.

To achieve bending fatigue test of steel wire rope, the basis of simple bending mostly used in application can be seen in Fig. 4. The drive sheave that moves the rope has a much bigger diameter than the test sheave so that, it is always the rope piece running over the test sheave that will break. Therefore, the distance between the sheaves is larger than the rope stroke so that the rope test piece does not move over the traction sheave. In Fig. 4, *1-3* are indicated the wire rope sample, test sheave and drive sheaves respectively. Drive sheave provides the movement of the wire rope and it has bigger diameter than test sheave. Constant tensile force applied from test sheave to wire rope sample. Breakage of the rope must occur in bending zone. For this reason, the test sheave must be smaller than drive sheave. In order to prevent contact of rope test zone and drive sheave the distance between drive sheave and test sheave should be minimum 30*d*, (d is diameter of rope), bigger than the rope stroke. In Fig. 4, *h* is the rope stroke, *l* is bending length, *u* is contact length between rope and sheave.

Test machine which is used to carry out bending experiment as shown in Fig. 5 consists of drive

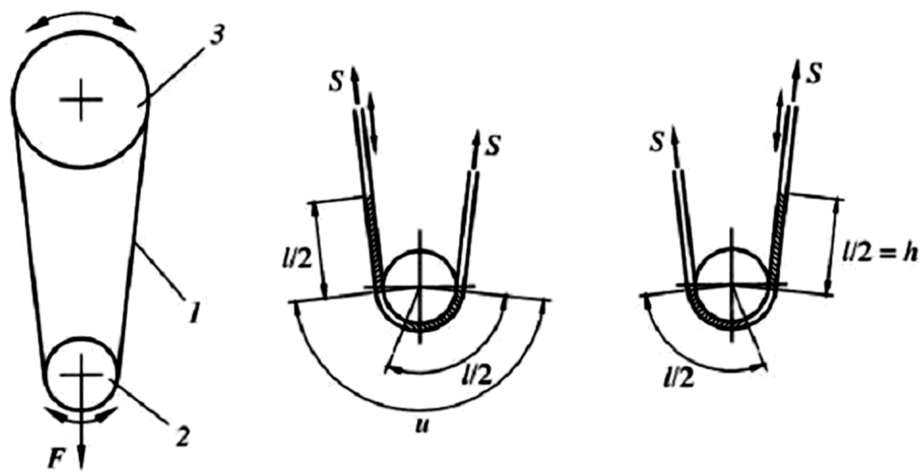


Fig. 4 — Simple bending.

Fig. 5 — Test machine for bending fatigue.

sheave, test sheave, electric motor, rotation speed adjustment button, leverage and several machine elements help it to run. Maximum rope force 30.0 kN, maximum diameter 16 mm maximum bending length is 800 mm. In order to compare test results bending over sheave test has been performed with two different sheave 250 mm and 170 mm in diameter. Rope samples are connected between drive sheave and test sheave by means of lead casting end connections. Leverage and a several of weights are used to maintain a constant tensile load S on the test sheave to static tensile load S can be applied to the rope tested permanently during the test. In this study two different tensile loads applied 17.0 kN and 11.7 kN these tensile loads have chosen according to Feyrer[1]. The bigger sheave is a drive sheave which moves with repeated length and smaller one is test sheave. Actual rope bending fatigue occurs at the contact length that is thirty times of rope diameter between test sheave and rope.

In the bending over sheave fatigue test, sheaves with 250 mm and 170 mm in diameter have been used, tensile loads 11.7 kN and 17.0 kN have been employed. Experiments were conducted with sheave to rope diameter ratio 25 and 17, and at rope tension of 11.7 kN and 17.0 kN. S/d^2 were 117 N/mm^2 and 170 N/mm^2. Four rope specimens were cycled to failure under each unique test condition non-corroded, rope under corrosion effect for one, two, and three weeks. In order to obtain comparable results according to rope tension, sheave diameter, and corrosion degree, parameters such as rotation speed, elastic stretch, wire grade, shape of sheave grove, lubrication etc. are kept same for all samples.

3 Results and Discussion

Bending over sheave test have been performed according to DIN 15020-2 standard. BoS fatigue lifetime results can be seen in Table 2. It can be concluded that BoS fatigue lifetime of 6x36 Warrington-Seale rope reduces as corrosion time increases. BoS fatigue lifetime reduces 30.4 % if tensile load is increased from 11.7 kN to 17.0 kN for with sheave to rope diameter ratio 25. Also BoS fatigue life time reduces 54.3% when tensile load is increased from 11.7 kN to 17.0 kN for with sheave to rope diameter ratio 17. The effect of tensile load has already examined by Onur and Imrak [3]. However aim of this study to determine effect of corrosion bending fatigue lifetime.

BoS fatigue life time reduces 28.64% if the rope sample keep in salt water solution for one week (for S/d^2=170 and D/d=25). BoS fatigue life time reduces 41.23 % if the rope sample keep in salt water solution for two weeks (for S/d^2=170 and D/d=25). BoS fatigue life time reduces 51.46 % if the rope sample keep in salt water solution for three weeks (for S/d^2=170 and D/d=25). BoS fatigue life time reduces 6.12 % if the rope sample keep in salt water solution for one week (for S/d^2=117 and D/d=25). BoS fatigue life time reduces 19.3 % if the rope sample keep in salt water solution for two weeks (for S/d^2=117 and D/d=25). BoS fatigue life time reduces 35.6 % if the rope sample keep in salt water solution for three weeks (for S/d^2=117 and D/d=25).

BoS fatigue life time reduces 28.34 % if the rope sample keep in salt water solution for one week (for S/d^2=170 and D/d=17). BoS fatigue life time reduces 36.6 % if the rope sample keep in salt water solution for two weeks (for S/d^2=170 and D/d=17). BoS fatigue life time reduces 48.2 % if the rope sample keep in salt water solution for three weeks (for S/d^2=170 and D/d=17). BoS fatigue life time reduces 11.79 % if the rope sample keep in salt water solution for one week (for S/d^2=117 and D/d=17). BoS fatigue life time reduces 28.73 % if the rope sample keep in salt water solution for two weeks (for S/d^2=117 and D/d=17). BoS fatigue life time reduces 33.8% if the rope sample keep in salt water solution for three weeks (for S/d2=117 and D/d=17).

In order to investigate the corrosion effect on both cases, 6 x 36 Warrington seale samples, which were kept in salty water for one to three weeks, have been

Table 2 — Experimental results.

Test number	S/d^2 (N/mm^2)	D/d	Parameters	Endurance N (cycles)	Fatigue life reduction %
Test 1	170	25	non-corroded	127900	
Test 2	170	25	1 week	91278	28.64 %
Test 3	170	25	2 weeks	75171	41.23 %
Test 4	170	25	3 weeks	62076	51.46 %
Test 5	117	25	non-corroded	181257	
Test6	117	25	1 week	170159	6.12 %
Test7	117	25	2 weeks	146288	19.3 %
Test 8	117	25	3 weeks	116721	35.6 %
Test 9	170	17	non-corroded	77066	
Test 10	170	17	1 week	55222	28.34%
Test 11	170	17	2 weeks	48854	36.6 %
Test 12	170	17	3 weeks	39856	48.2 %
Test 13	117	17	non-corroded	168698	
Test 14	117	17	1 week	148800	11.79%
Test 15	117	17	2 weeks	120222	28.73%
Test 16	117	17	3weeks	111554	33.8%

used. It shows when the corrosion level increases, fatigue endurance of wire rope decreases dramatically in every condition. However, the sensitivity of corrosion increases when the tensile load increase, due to the synergistic effect of corrosion and tensile load. According to obtained results, lifetime of the rope reduces, when smaller sheave used in the BoS tests. But, the reduction levels are almost same for different sheave with different diameter. It can be concluded that pre-corroded wire rope are not very sensitive to the change in diameter ratio.

4 Conclusions

The BoS fatigue tests were successfully accomplished for 6 x 36 Warrington Seale rope, and the evaluation of different corrosion pattern was studied. The objective of this investigation was to assess the viability of a total fatigue life prediction methodology for material with pre-existing corrosion damage. In addition to this, the effect of the sheave diameter (D), and tensile load (S) examined successfully. If the ratio D/d reduces from 25 to 17 the life time of the rope reduces the endurance of wire rope reduces 39.74 % (for S=17.0 kN). When the shave diameter (D)is 250 mm if tensile force (S) increases from 11.7 to 17.0 kN, the endurance of wire rope reduces 29.43 %.

The experimental result is valid for 6 x 36 Warrington Seale wire rope, which are mostly exposed to atmospheric effect. It shows when the corrosion level increases endurance of wire rope decreases dramatically in every condition. However the sensitivity of corrosion increases when the tensile load increase, because of the synergistic effect of corrosion and tensile load. There is various type of wire rope available in service and most of them using in corrosive environment. Future works need to concentrated on the description of the relationship between corrosion level and wire rope construction.

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