

İSTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**MODELLING AND ANALYSIS CORROSION FATIGUE BEHAVIOUR OF
STEEL WIRE ROPE**



Ph.D. THESIS

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Department of Mechanical Engineering

Mechanical Engineering Programme

September 2016

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**ÇELİK TEL HALATLARIN KOROZYONLU YORULMA DAVRANIŞININ
MODELLENMESİ VE İNCELENMESİ**

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To my family,



FOREWORD

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ABBREVIATIONS

IWRC	: Independent Wire Rope Core
ESWRC	: Steel Core Coated with Solid Polymer
PWRC	: Steel Core Parallel to External Strand
BoS	: Bending Over Sheave
W	: Warrington
WS	: Warrington Seale
WSC	: Wire Strand Core
FC	: Fibre Core
F	: Filler
PP	: Polypropylene
PA	: Polyamide
DIN	: Deutsches Institut für Normung
ISO	: International Organization for Standardization
BS	: British Standards
ANSI	: American National Standards Institute
AISI	: American Iron and Steel Institute
ASTM	: American Society for Testing and Materials
TS	: Turkish Standards
wt	: Weight



SYMBOLS

D	: Sheave diameter
d	: Nominal diameter of wire rope
D/d	: Diameter ratio
S	: Tensile load
S/d²	: Specific tensile load
N_{sim}	: Simple bending
N_{rev}	: Reverse bending





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MODELLING AND ANALYSIS CORROSION FATIGUE BEHAVIOUR OF STEEL WIRE ROPES

SUMMARY

Steel wire rope is a critical component in many engineering applications, including cranes, lifts, mine hoisting, bridges, cableways, offshore mooring systems, where is mostly subjected to dynamic loads. Although there are many different compositions 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 rope, 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 greater flexibility of the six strand types of compositions lends well to running rope application.

It is well known that a major advantage of such elements is their capacity to support large axial loads with comparatively small bending or torsional stiffness. In nearly all service applications a wire rope will be subjected of dynamic load which causes fatigue. Fatigue loading may 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 (BoS) or bending fatigue. The great majority of applications, e.g. cranes, lifts, and winches will subject the rope to bending fatigue.

Although there are many studies, which have examined the fatigue life prediction based on initial state of the wire rope, it has observed that the wire rope might rupture before the stated fatigue life. The reason of this mostly about the running condition. When the wire rope runs under the atmospheric influences, the fatigue life estimation of it usually not valid. In order to determine the exact lifetime of wire rope, degradation influence such as corrosion, wear, broken wire etc. must be considered.

This thesis shows the combine effect of corrosion and fatigue on wire ropes. It reports the outcome of a series of test undertaken on 6 x 36 Warrington-Seale ropes, and 32 Warrington (W) x 7 rotation resistance ropes, in order to determine their exact fatigue endurance under different conditions. The reason of using two different types of wire rope composition is to show the difference the corrosion influence with respect to way of twisting strands and wires.

One of the mayor degradation parameter on wire rope is corrosion. In order to determine corrosion effect on wire rope, all the samples have kept in salty water solution, which consists of 5% salt and 95% water. Then bending fatigue tests have performed for each wire ropes with different level of corrosion, and the data have compared with the reference test results.

The other important parameter is tensile load. When the tensile load increases, the fatigue lifetime decreases. However, it is important to determine how much the wire

ropes effected by the combination of increasing tensile load, and increasing corrosion level.

Another crucial parameter, which examined in this thesis, is diameter ratio D/d . Use a smaller sheave causes the decline on wire rope lifetime. Wire ropes with different level of corrosion have tested in two different sheave diameter.

This thesis organized as follows: In the introduction section, available studies about wire ropes have presented and their missing points have discussed. In the next sections, available wire ropes and their properties, important parameters, which are effected lifetime of wire rope, and discard criteria have explained respectively. Further section includes the information about test machines and its components, and specimen properties, which have chosen for this study. Final section includes the results and outlines the most important conclusions.



ÇELİK TEL HALATLARIN KOROZYONLU YORULMA DAVRANIŞININ MODELLENMESİ VE İNCELENMESİ

ÖZET

Tel halatlar; asansör, vinç, köprü, teleferik gibi sistemlerde maden işletmelerinde, denizcilikte yük kaldırma ve iletme elemanı olarak yaygın kullanılan ve dinamik yükler altında yüksek derecede zorlanan önemli elemanlardan biridir. Uygulama alanı çok geniş olan tel halatlarda, çalıştırılmaları esnasında belirli bir zaman aralığında meydana gelen mekanik yorulma ve bozulma olaylarına bağlı hasar mekanizmalarının oluşması ve ilerlemesi oldukça karmaşık bir konudur.

Tel halatların çalışmaları sırasında yorulmaya neden olacak genel olarak iki çeşit yükleme durumu mevcuttur. Bunlar; çekme-çekme yorulması ve makara üzerine sarılması nedeniyle oluşan eğilme (bending over sheave) yorulmasıdır. Çekme-çekme yorulması, değişken bir çekme yükünün varlığıyla tel halat üzerinde meydana gelen yorulmadır. Eğilme yorulması ise tel halatların büyük bir uygulama alanı bulduğu vinçler ve asansörlerde olduğu gibi statik bir çekme yüküne karşılık tel halatın makaralara sarılmasından (Bending over Sheave, BoS) dolayı meydana gelen dinamik tekrarlı eğilmenin oluşturduğu yorulmadır. Dinamik yüklere maruz tel halatlarda sonlu bir ömür ve farklı ortam ya da farklı çalıştırılma koşullarında ömür kısalması söz konusudur.

Yorulma konusunda günümüze kadar klasik silindirik deney numuneleri üzerinde yapılan deneysel çalışmalar sonucunda malzemenin yorulma ömrüne etki eden parametreler belirlenmiştir. Ancak korozyonlu yorulma konusunda klasik silindirik deney numuneleri üzerinde yapılan deneysel çalışmaların sonuçlarına göre belirlenmiş olan bu parametrelerin bazılarının etkisinin farklı yönde olduğu gözlemlenmiştir. Literatürde klasik silindirik deney numuneleri kullanılarak yapılmış yorulma ve korozyonlu yorulma deneylerine sıklıkla rastlanmaktadır. Buna göre normal yorulma deneylerinde etkin parametrelerin, korozyonlu yorulma deneyleri sonuçlarına göre aynı oranda etkin olmadığı söylenebilir.

Tel halatlarda ise yapı klasik deney numunelerinden çok daha karmaşıktır. Bu nedenle gerek yorulma deneylerinin gerekse korozyonlu yorulma deneylerinin neticeleri doğrultusunda tel halatların ömrüne etki eden parametreleri yorumlamak oldukça karmaşık bir konudur. Literatürdeki çalışmalar incelendiğinde ömrü bilinen bir halatın, çalıştırıldığı ortama göre, beklendiğinden çok daha kısa sürede ömrünü tamamladığına dair sonuçların var olduğu görülmüştür. Bu durum emniyetli ve ekonomik çalışma koşulları bakımından incelenmeye değer bir konudur.

Bu doktora tez çalışmasında incelenen yorulma türü eğilme yorulmasıdır. Kullanım yerlerine göre çelik tel halatlar, makaralar üzerinde sarılarak çalışmaları nedeniyle eğilme yorulmasına maruz kalmaktadır. Literatürde tel halatlarda eğilme yorulması ile ilgili pek çok çalışma bulunmasına karşın, tel halatların çalışma koşulları gereği kaçınılmaz olan korozyonun halat yorulma ömrüne etkisinin araştırıldığı bir çalışmaya rastlanmamıştır. Korozyonlu yorulma konusunda yapılmış olan çalışmalar ise genellikle klasik silindirik deney numuneleri üzerinde çalışılmış ve hasar mekanizmaları incelenmiştir.

Klasik silindirik deney numuneleri kullanılarak yapılan yorulma veya korozyonlu yorulma deneyleri ile çelik tel halat numuneleri kullanılarak yapılan yorulma deneylerini birbirinden ayırmak gerekir. Klasik deney numuneleri ile yapılan yorulma deneylerine göre çatlak çekirdeklenmesinin genellikle parça yüzeyinden başladığı bilinmektedir. Ancak çeşitli şekillerde örülerek veya bükülerek bir araya getirilmiş çok sayıda telin teşkil ettiği halatlarda tek bir yüzey varlığından söz edilemez. İç tellerin birbiri ile teması nedeniyle oluşan kazınmalı aşınma bölgesi de çatlak çekirdeklenmesine sebep olabilir. Bu nedenle tel halatlarda çatlak çekirdeklenmesinin daima dış yüzey bölgesinde oluşabileceğini söylemek doğru bir yaklaşım olmaz. Dolayısıyla hasar mekanizmaları açısından da, klasik deney numuneleri ile tel halatlar arasında önemli farklar olduğu görülmektedir. Bu nedenle klasik silindirik deney numuneleri ile yapılan korozyonlu yorulma deneylerinin neticelerini kullanarak tel halatlarda benzer kabuller ile yaklaşım yapmak doğru değildir.

Çalışma koşulları gereği korozyona maruz kalan tel halatlarda eğilme yorulmasında etkin parametrelerin belirlenmesi ile halat ömrünün daha doğru tespit edilebilmesi mümkün olacaktır. Bu durum hem halat imalatçıları açısından hem de çalışma güvenliği ve standart bir muayene metodunun tespit edilebilmesi açısından kritik bir öneme sahiptir.

Bu doktora tez çalışmasında, halat eğilme yorulma ömrüne korozyonun etkisini inceleyebilmek için halat numuneleri %5 tuz, %95 su bulunan ortamda belirli sürelerde tutulmuştur. Ön korozyon oluşturma aşaması sonucunda 6 x 36 Warrington-Seale halatların 32 (W) x 7 dönme dirençli halatlara göre korozi ortamdan daha hızlı etkilendiği görülmüştür. 32 (W) x 7 dönme dirençli halat konstrüksiyonu teşkil edilirken teller üst üste sarıldığı için korozyonun iç tellere ulaşması için daha fazla zamana ihtiyaç duyulmuştur. Böylelikle aynı ortam koşullarında tutulan iki farklı konstrüksiyona sahip halatın korozyondan etkilenme seviyeleri incelenmiştir. Ön korozyonlu çelik tel halatların yorulma ömrünün kıyaslanabilmesi için her iki halat konstrüksiyonu da aynı korozyon hücresinde belirli sürelerce bekletilmiştir. Ayrıca her iki halat türü için aynı çekme yükü ve aynı makara çapı seçilmiştir.

Buna ek olarak, diğer tüm parametreler sabit tutularak, 17.0 kN ve 11.7 kN olmak üzere iki farklı çekme yükü uygulanmış ve sonuçlar değerlendirilmiştir. Böylece çekme yükü değişimi ve korozyon seviyesinin birleşik etkisi araştırılmıştır.

Halat eğilme yorulma ömrü üzerinde bir başka etken parametre ise test makarasının çapıdır. Test makarasının çapındaki değişimin korozyonlu numuneler üzerindeki etkisini incelemek için 250 mm ve 170 mm olmak üzere iki farklı çapta makara kullanılmıştır. Her bir korozyon seviyesi, halat konstrüksiyonu ve çekme yükü için deneyler tekrar edilmiştir.

Birinci bölümde, literatürde tel halat yorulması ve korozyon konusunda bu çalışmaya referans olabilecek çalışmalar anlatılmıştır.

İkinci bölümde, çelik tel halatların genel yapısı, kullanım alanları, imalatı, mekanik özellikleri, konstrüksiyon şekilleri, halat malzemeleri detaylı olarak anlatılmıştır.

Üçüncü bölümde, tel halat ömründe etkili parametreler sıralanmıştır. Bu parametreler hakkında literatürde yer alan çalışmalar sunulurken her bir parametre ayrı ayrı tanımlanmıştır. Bu bölümde halat ömrüne etki eden faktörlerden çekme yükü (S), çap oranı (D/d), halat çapı (d), eğilme türü, halat türü, tel anma dayanımı, halat yuvası şekli, halat yuva malzemesi, tel halat kalınlığı, yağlama, işletmede tekrar yağlama, korozyon, halat sarılma açısı, halat kenar sapması, halat öz tipi, sapma açısı, özel halat kullanımı gibi faktörler irdelenmiştir.

Dördüncü bölümde tel halatların imalatı ya da çalıştırılması sırasında oluşabilecek halat kusurları tariflenmiştir. Tel halatların servis dışı bırakılması için standartlarda belirtilen izin verilebilir maksimum hasar mertebeleri sunulmuştur. Bu bölümde açıklanan halat kusurları başlıca aşınma, korozyon, halat çapında azalma, demet kopması, tel kopması, elastikiyetin azalması, şekil değiştirme, dalgalanma, kafes oluşumu, demet çıkması, tel çıkması, halat çapında bölgesel büyüme/küçülme, yassılaşıma, kıvrılmalar veya gerilmiş ilmekler, bükülme yetersiz yağlama, ısı sebebiyle hasarlanma, tel kırık sayıları ve bu kırık tellerin halat içindeki dağılımı, martenzitik geçrekleşme ve dış etkiler nedeniyle oluşan hasarlar olarak sıralanabilir.

Beşinci bölümde, çelik tel halatlar üzerinde farklı seviyelerde korozyon oluşturulmuş ve bu korozyon seviyeleri gösterilmiştir. Eğilme yorulması deneylerinde kullanılan test makinası ve bileşenleri detaylı olarak anlatılmıştır. Ayrıca kullanılan tel halat numunelerinin mekanik özellikleri anlatılmış ve deneylerde kullanılan parametreler seçilme nedenleriyle birlikte sunulmuştur. Ön korozyon oluşturulmuş halat numuneleri eğilme yorulma testine tabi tutulmuş ve deneysel sonuçlara göre, korozyon miktarı artışının yorulma ömrüne etki eden diğer parametrelerle ortak etkisi anlatılmıştır.

Son bölümde, deneylerden elde edilen sonuçlara göre korozif ortamda çalıştırılan tel halatların dinamik yükler altında davranışı yorumlanmıştır. Sonuçlar özetlenmiş ve gelecekte bu konuda çalışacak olan araştırmacılar için tavsiyeler sunulmuştur.



1. INTRODUCTION

Steel wire ropes constitute a wide class of important engineering component. They comprise groups of wires spun helically together in a regular geometric pattern to form an integral unit to provide axial strength and stiffness. It is well known that a mayor advantage of such elements is their capacity to support large axial loads with comparatively small bending and torsional stiffness.

Due to its complex geometry, a wire rope is subjected to the combined effects of tension, shear, bending, torsion, contact friction and possible local plastic yielding when loaded.

In this study, endurance of the wire ropes under dynamic load, and corrosion effect are investigated experimentally. It is not possible to define the lifetime of wire ropes with the conventional test method because of the wire ropes have different section and composition in comparison with regular material.

1.1 Purpose of Thesis

This doctoral thesis, aims the call attention to combine effect of corrosion and fatigue, which are inevitable in most cases, on wire ropes. To achive this purpose, series of tests undertaken on 6 x 36 Warrington-Seale and 32 Warrington (W) x 7 rotation resistant ropes to investigate the effects of corrosion on the wire rope's Bending-over-Sheave (BoS) fatigue endurance. In the literature, wire ropes total fatigue life prediction methodologies have examined based on the initial condition of the wire rope. However, wire ropes frequently exposed to atmospheric influences. In order to determine the exact lifetime of wire rope degradation influence such as wear, corrosion, broken wire etc. should be consider.

In this thesis 6 x 36 Warrington-Seale wire rope samples have kept in the %5 wt. salt water for one, two, three weeks, and 32 (W) x 7 soliflex rotation resistant rope samples have kept up to twelve weeks, and the data compared with the reference test results. Beside that, pre-corroded wire rope samples were cycle to failure at two different tensile loads and two different sheaves diameter. According to the result of these

experiments, if corrosion exposure increases, total lifetime of wire rope decreases. The dispersion from shortest to longest fatigue lives among the different corrosion conditions decreased at the higher stress levels. The main conclusion from this thesis was that total fatigue life prediction method has shown to be a mostly successful tool in predicting the life of pre-corroded test specimens, while capturing the effects different tensile load and corrosion levels.

1.2 Literature review

In the literature, various investigations have performed in order to determine effect of bending fatigue (BoS) to the lifetime of the steel wire ropes. Feyrer (2007), examined the effects of various parameters (tensile load, diameter ratio, diameter of rope, bending length, core type, zinc coating, lubrication, sheave geometry and materials, winding angle, reverse bending, material, and side deflection,) on the rope's (BoS) bending fatigue lifetime. He presented the experimental test results of steel wire ropes subjected to BoS fatigue. Onur & Imrak (2012), investigated effects of the tensile load (S), rotation speed, and diameter of sheave (D) to the BoS fatigue endurance of wire ropes. They used 39 strands rotation resistant rope and 6 x 36 Warrington Selaie rope in the experiments. They discussed the rotation speed and tensile load according to the change of wire rope composition and sheave diameter. They provided a contribution to the literature by making regression analysis on Feyrer's theoretical ropes fatigue equation. Onur & Imrak (2013), examined the effects of wear, internal and external wire breaks, which are occur during the service, on bending over sheave fatigue life of 6 x 36 Warrington Seale wire ropes. Beside, they made experiments to investigate the effects of abrasive wear, insufficient lubrication, curling, which might occur manufacturing process or because of misuse of ropes. They created artificial damage on the wire rope sample and examined the effects of these degradation parameters. Giglio & Manes (2003), investigated the effect of winding angle on bending fatigue lifetime. For this, they used 19 x 7 rotation resistant rope 4.76 mm in diameter, preforme ropes, which used in aircraft rescue hoist, that has nineteen strands and each strand has seven wires. They have presented relation with winding angle and wire rope bending fatigue in quadratic form. According to this, when the tip of the rope oscillate $\pm 28^\circ$ stated wire rope has infinite life. Torkar & Arzensek (2002), conducted bending fatigue tests of wires located in outer strands of 6 x 19 Seale rope. Chaplin et al. (1999),

reported effects of rope composition, lay and core types, to the rope's lifetime by using Bridon rope Inc.'s test data. They concluded that ropes had more flexibility and superior endurance limit when ropes having more external wires and external strands were used. In addition to this, when fibre core was used lang lay ropes had longer lifetime than regular lay ropes. Ridge et al. (2001), examined the effects of degradation (wire breaks, abrasive wear, plastic wear, slack wires, torsional imbalance, corrosion, slack strands) to the BoS fatigue endurance of steel wire ropes. For this, they created these damages on wire ropes before the experiment and observed the effects on lifetime. They compared the results with Feyrer's theoretical fatigue equations. Gorbatov et al. (2007), investigated the effects of some parameters (type of wire rope core, tensile load, type of core lubricant) on bending fatigue lifetime of 6 x 36 Warrington-Seale rope with 16 mm diameter. They applied three different tensile loads on 6 x 36 Warrington Seale rope, and used test sheave with 400 mm in diameter. According to test results they concluded when the wire rope core lubricate with ASKM-1A, has longer fatigue life than when it lubricate with E-1. Schönherr (2005), studied the effect of fleet angle of steel wire ropes subjected to BoS fatigue. He made necessary bending tests to define the growth in number of broken wire, and fatigue life, for this, he used lang lay rope with 12 mm and 16 mm in diameter. In order to observe the effect of parameters he changed the wire rope composition, diameter of wire rope, fleet angle, bending length for each tests. He concluded that in the presense of fleet angle, bending fatigue lifetime of a rope change according to wire rope compositions, especially wire rope with higher torsional stiffness, it decreases dramatically. Ridge et al. (2000), identified the strain and its distrubition of steel wire rope subjected to bending fatigue by sticking strain gage on various place on each wires. They used two different type of rope one of them 6 x 25 RHL filler strand and the other 6 strand IWRC. The technical properties of rope samples are; rope diameter 19 mm, length of the rope 1.7 m, bending length 150 mm, diameter ratio 18:1, rope speed 0.03 m/s. According to obtained results, they concluded that the cyclic strain of the rope is maximum when it goes on a sheave and it has significant relation with the fatigue endurance. They observed generally small fluctuations apart from these sharp peaks.

In the literature experimental studies about wire rope fatigue split into two main categories tension- tension fatigue, bending over sheave. Investigated parameter are tensile load (S), sheave dimaeter effect (D/d ratio), insufficient lubrication, fleet angle

wear, broken wire, and so on. However, wire ropes usually exposed to atmospheric effect that causes corrosion. In this study, corrosion effects of steel wire rope, which is inevitable under the atmospheric circumstance is examined experimentally. Nevertheless, corrosion and fatigue behaviour is examined for various type of conventional materials sample. Various researchers have studied the mechanisms of corrosion in terms of microstructural and environmental influences.

Gruenberg et al. (2004), investigated fatigue life of pre-corroded 2024-T3 aluminum. They used aluminum alloy 2024-T3 specimens that are exposed to corrosion, and tested in a special laboratory setting. The test specimens kept in corrosive environment, for 6, 24, 72 hours in three specimen orientations. They applied dynamic loads at three different stress levels to the corroded samples. They concluded that the fatigue lifetime of the aluminum sample decreases dramatically when the pre-corrosion time increases. Chamos et al. (2010), conducted 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. (2000), examined in aging aircraft, the synergetic interaction between corrosion and fatigue. It has shown to reduce the life expectancy of aluminum alloys. The fatigue life of the specimens decreased in an inverse exponential fashion as mass loss per unit area increased. Besides the hardness values of the corroded surfaces were observed to drop. Burns et al. (2010), 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 modelled using crack surface microscopic analysis and a fracture mechanics tool. Jones & Hoepfner (2005), investigated pit-to-crack transition experimentally. 1.600 mm and 4.064 mm 7075-T6 aluminum alloy specimen were corroded using a 15:1 ratio of 3.5% NaCl solution and H₂O₂ prior to fatigue loading. Cracks initiating from corrosion pits have investigated visually in order to understand how pit-to-crack transitions occur.

As it can be seen the literature, corrosion is an inevitable problem for almost all kind of metals. Authors generally investigated the effects of pre-corrosion on aluminum alloy. There are limited research about combine effect of corrosion and fatigue on steel. Begum et al. (2011), examined corrosion fatigue behaviour of four types of austenitic

stainless steels were investigated in boiling 45% magnesium chloride solution at frequency of 0.1 Hz and stress ratio of 0.25. 316LN type stainless steel possessed the best resistance and type 304 stainless steel had the lowest resistance to corrosion fatigue. However, obtained results from the pre-corroded fatigue tests of a regular test sample (standard diameter, polished surface, without any notch on the surface) cannot be directly apply to the wire ropes even if it has made by the same materials. Due to complex geometry of a wire rope, fatigue tests have to be performed with special test equipment. Beside, pre-corrosion creation stage must be done by special equipment as well.

In the following chapter, basic information about wire ropes properties, materials, manufacturing, and its strand compositions are given.

In the third chapter, factors effecting fatigue life of wire ropes, such as diameter ratio (D/d), tensile load, bending type, groove type, groove material, diameter of rope (d), wire rope composition, diameter of rope's wire, lubrication, corrosion, fleet angle, core type are described with the references from literature.

In the fourth chapter, rope defects and damage types, that might occur during manufacturing or in operation are explained. Besides, discard criterias and maximum allowable detects which specified in standards are explained. In this chapter, discard criterias (wear, reduction of rope diameter, corrosion, decreased elasticity, fracture of strands, deformations, birdcage, waviness, strand extrusion, wire extrusion, localized increase or decrease in diameter of rope, flattened portions, loop formations, kinks, nodes, loose wires, bends, misplaced outer wires, insufficient lubrication, damage due to heat or electric arcing, broken wires, damage caused by heat) are discussed in detail. In the fifth chapter, wire rope composition, which used in the experiment and their technical properties are explained. Bending over sheave test machine, which is manufacture for these purpose particularly explained. Then corrosion procedure and wire rope preparation procedure explained in detail. Combine effect of corrosion and fatigue are investigated experimentally. The results are presented according to different parameters.

In the last section, pre-corroded wire ropes fatigue endurance evaluated according to different wire rope compositions, diameter ratio, and tensile load.



2. WIRE ROPES

2.1 Introduction

Wire rope has invented in 1834 by *Wilhelm August Julius Albert*. He has installed a wire rope of his own manufacture in a mine in Germany. Ever since, wire rope has been used in a various number of ways, which contain hauling and transporting, in general engineering, for cranes, elevators and aerial ropeways, and also in automobile and aircraft engineering, bridge construction, and as a structural support (Sturgeon, 1990).

Improvement in the manufacture of the raw material, steel used for the wires in wire ropes have changed the product we use today quite markedly, but research into tensile stresses in the wire rope, life of wire rope, rope composition, dimensioning, and discard criteria, and the operation and application of wire rope is helping to ensure that the product we use is getting better and better.

Wire ropes consist of individual parts wires, strands and cores. They interact with each other during operation. Engineers design those individual parts in different finishes, steel grades, and a many kind of compositions to achieve the best balance of strength, crush resistance, abrasion resistance, bending fatigue resistance, corrosion resistance for each application. In order to choose the most suitable wire rope for each application, the necessary performance characteristics for the job has to known. The three characteristics of a wire rope to consider are; flexibility, strength, robustness.

In all dynamic rope applications (as opposed to static applications such as guy wires etc.) the choice is invariably a compromise (Demirsoy, 1991).

Strength can be increase by increasing the diameter of the wire rope and/or increasing the tensile strength of the individual wires and/or increasing the cross sectional steel content (by decreasing the air voids between the wires) and/or using a steel core composition (Cookes Limited, 2007).

In order to increase flexibility more wires of a smaller diameter can be used and/or decreasing the tensile strength of the individual wires and/or using a fibre core.

Robustness, can be increased, by using fewer wires of a larger diameter and/or using a steel core and/or by increasing the steel area exposed to sources of external damage. To protect the wire rope against corrosion coatings such as galvanizing can be applied. With the development of wire ropes, chain which previously was using as a hoisting element lost its priority. The reason of using a wire rope instead of chain listed as follows:

- Because of the lightweight of wire ropes, mass influence is less than the chains.
- It provides safer operation and easy operation control.
- Wire ropes are much more flexible than chains, so they have more resistance against to impacts.
- They can work quiet at high speed.
- Unit price is cheaper than the chains.
- Sudden rupture can be avoided by observing the broken wires (Cooke's Limited, 2007).

2.2 Wire Rope Terminology

Wire rope consists of a number of strands laid up usually over a central core. Each strand is made from a number of individual wires. The wires are helically laid together to form a strand. Then the required number of strand are helically closed together around the core to form a wire rope (Figure 2.1), (Demirsoy, 1991).

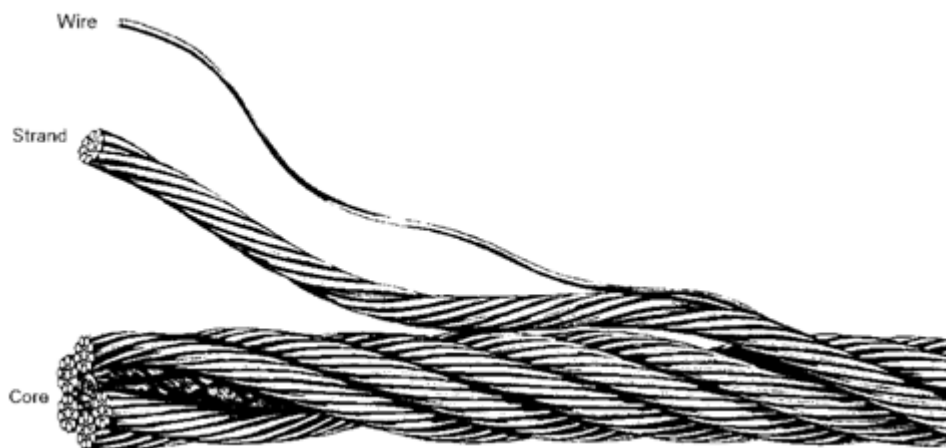


Figure 2.1 : Components of a rope (BS 6570, 1986).

An analysis of wire ropes will show that most are composed of a number of strands laid around a core. The strands consist number of wires. The number of strands and wires are the chief characteristic of the composition of a wire rope (Figure 2.2).

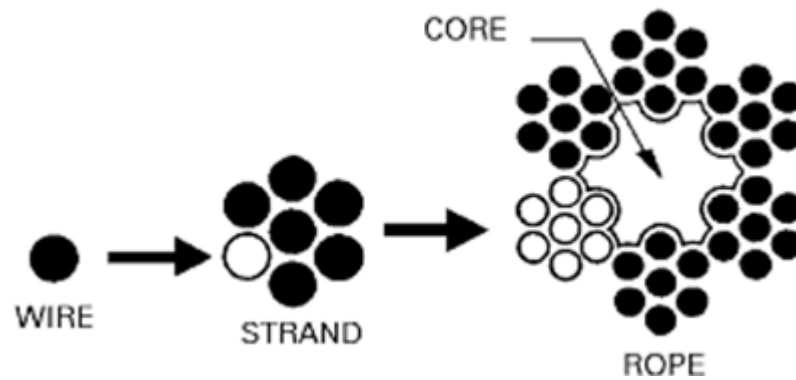


Figure 2.2 : Cross sectional view of wire rope's components.

Wire ropes are used in various different applications and it creates a requirement for a large number of different compositions to be manufactured.

The composition of a wire rope is defined by;

- The number of strands,
- The number of wires in each strand,
- The type of cores.

2.2.1 Cores

There are generally two types of core, fibre and steel. Basically, all serve the same purpose. The main purpose of using of the core in the center of a wire rope is to keep the strands in their correct position so that a load remains evenly distributed over all strands. The core supports the strands of the rope. It must be the accurate size to avoid contact between the strands when the rope is loaded.

Fibre cores (FC) can be either natural or man-made fibre. Certain man-made fibres (e.g. polypropylene) have the advantage that they neither absorb nor retain moisture. A wire rope with a fibre core would be much more flexible than a rope with a steel core, and could therefore be used on smaller sheaves. A new rope with a fibre core might be more flexible than a similar rope with a steel core, but this flexibility does not result in a longer life in a rope subject to bending fatigue. The flexibility is soon lost, since the compression of the core causes the strands rubbing against each other, in this way reducing flexibility.

A steel core is usually an independent wire rope core (IWRC) around which the outer strands are laid. Rope sizes smaller than 13 mm diameter. For many uses, a wire rope with an independent wire rope core is recommended. The core of these ropes is commonly made up of 6 strands of 7 wires each around a centre strand, also of 7 wires.

The independent wire rope core provides permanent support and uniform spacing of the strands laid around it. It is not compressed and has a greater wear resistance than a fibre core. Besides it provides permanent elastic stretch of the wire rope over a long period, increased resistance to crushing and deformation, and increased breaking load (about 8% in a 6 strand rope and 25% in an 8 strand rope). Additionally, the lubricant does not get squeezed out of an independent wire rope core, so it does not contribute to internal corrosion as a fibre core can (BS 6570, 1986).

Although a new rope with an IWRC may be less flexible than a new rope with a fibre core, it retains its relative flexibility. However, a rope with a fibre core loses its flexibility during service. Because of it has better resistance to crushing and deformation, a rope with an IWRC is less sensitive to damage when used on small diameter sheaves and drums than a rope with a fibre core. It will also proceed much longer if wound on a drum with more than one layer. Due to its compressibility, a rope with a fibre core will soon lose its elastic stretch, but with an IWRC the elastic stretch is retained. The opinion that fibre cored ropes will absorb shock loads better has been disproved by the facts.

As a rule the direction of lay of a wire rope core is the same as that of the rope, i.e. a right lay wire rope has a right laid IWRC etc. If the rope is untwisted, the core will become longer and if the wire rope is twisted more tightly, the core will also shorten. If the rope and the IWRC were twisted in opposite directions, forces disposing to tighten or loosen the lay would have the opposite effect on the core, which could lead to failure of the core. The core is however, laid in such a way as to prevent the wires in the strands crossing those in the core and causing damage. In a regular lay wire rope the core is often Lang's lay and in a Lang's lay rope the core is regular lay.

However, a wire strand core (WSC) might be used. Size for size, a rope with a steel core is stronger than a rope with a fibre core. A rope with a steel core is more resistant to crushing, deformation, and stretch than a fibre cored wire rope. For some applications it is essential to keep the elastic stretch of the rope as low as possible, e.g. ships rigging. A core consists of a single strand with the same number of wires as the other strands will reduce the elastic stretch to a minimum. A wire strand cored wire rope has a low flexibility: it is therefore not suitable as a hoist rope. It is commonly seen in small diameter ropes (known to some as aircraft cable) where the size makes an IWRC impractical (BS 6570, 1986).

Almost all wire rope is laid up over a core, Fibre Core (natural or synthetic) (FC), Independent Wire Rope Core (IWRC) or Wire Strand Core (WSC) (Figure 2.3).

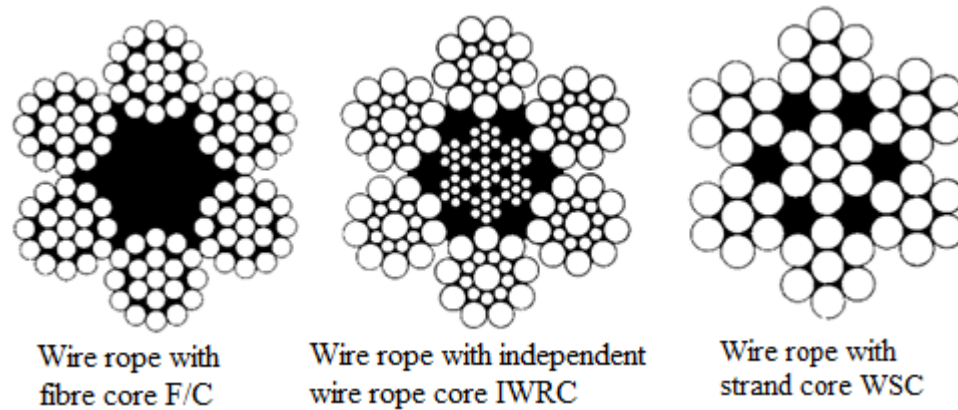


Figure 2.3 : Type of cores (BS 6570, 1986).

2.2.2 Strands

In order to provide the desired resistance to fatigue and abrasion, strands are designed with various combinations of wires and wire sizes. In general, a large number of small wires will be more fatigue resistant and less abrasion resistant than a small number of large wires (Figure 2.4).

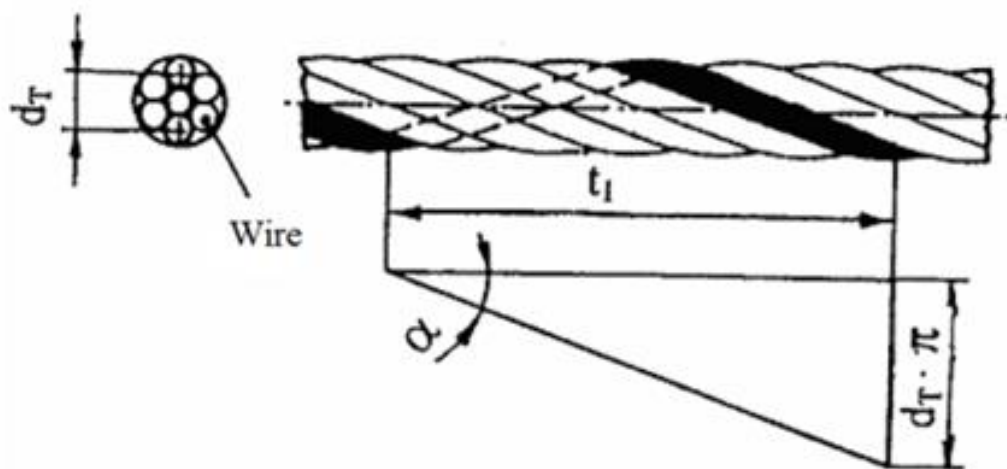


Figure 2.4 : Quantities of a strand (Cürgül, 1995).

Single size; Wires in same diameter wound around a center and they creates single size strands (Figure 2.5) (Union, 2016).

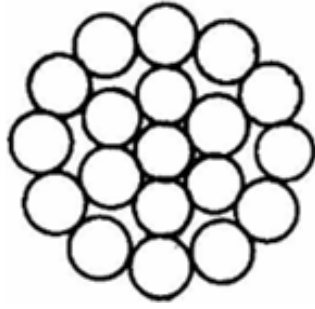


Figure 2.5 : Single size strand.

Seale; large outer wires with the same number of small inner wires around a core wire (Figure 2.6). Seale strand provides great abrasion resistance whereas less fatigue resistance. It provides excellent crush resistance over drums when used with an IWRC (Union, 2016).

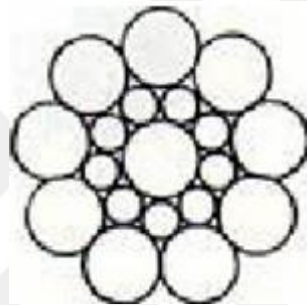


Figure 2.6 : Seale strand.

Filler; provides flexibility, a good balance of strength, crush resistance, and resistance to abrasion small wires fill spaces among large wires (Figure 2.7) (Union, 2016).

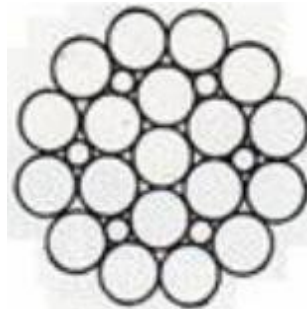


Figure 2.7 : Filler strand.

Warrington; outer layer has small and large wires (Figure 2.8). It provides good strength and flexibility but low crush resistance and abrasion (Union, 2016).

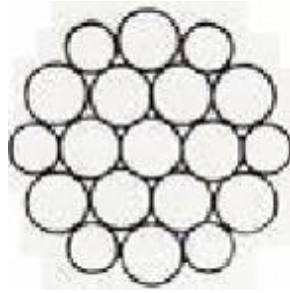


Figure 2.8 : Warrington strand.

Warrington Seale; are characterized by in comprasion with big number of wires in strands and therefore it has high flexibility. In the outer layer of the rope wires in bigger diameter and they provide its successful application under conditions of corrosive environment and abrasive damage (Figure 2.9) (Union, 2016).

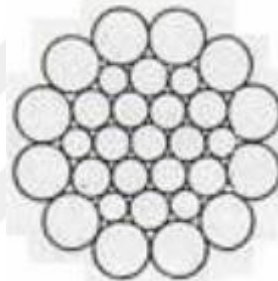


Figure 2.9 : 6 x 31Warrington Seale strand.

Seale Filler; in the inner layer and outer layer have same amount of wires however inner layers have Filler wires (Figure 2.10) (Union, 2016).

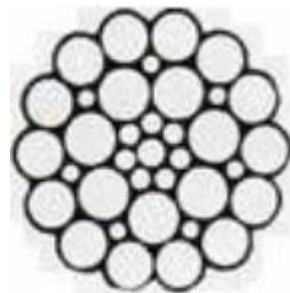


Figure 2.10 : 6 x 36 Seale Filler strand.

Seale filler wire Filler Seale wire Warrington Seale many frequently used wire ropes use combinations of these basic compositions.

Multiple operation; is formed by one of the above strand designs may be covered with one or more layers of uniform sized wires (Figure 2.11).

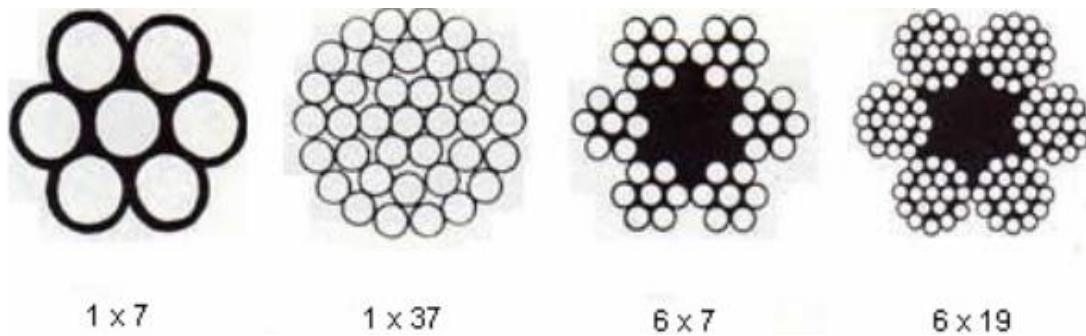


Figure 2.11 : Multiple operation strand.

2.2.3 Rope Lay

Regular lay: The wires wound in one direction and the strands wound in the opposite direction. It provides resistance to untwist and kink, has more crush resistance than Lang lay. It is easier to handle.

Lang Lay: Wires and strands wound the same direction. It has excellent flexibility, resistance to abrasion, and fatigue resistance than regular lay however, it will kink and untwist.

Right lay: Wire rope composed by wrapping strands to the right direction around the core. It is commonly used.

Left lay: Wire rope composed by wrapping strands to the left direction around the core. It used in a number of special situations for example cable tool drilling line (Figure 2.12).

Alternate lay: Alternate strands of right Lang and regular lay. Combines the best characteristic of Lang and regular lay for winch lines or boom hoist (BS 6570, 1986).

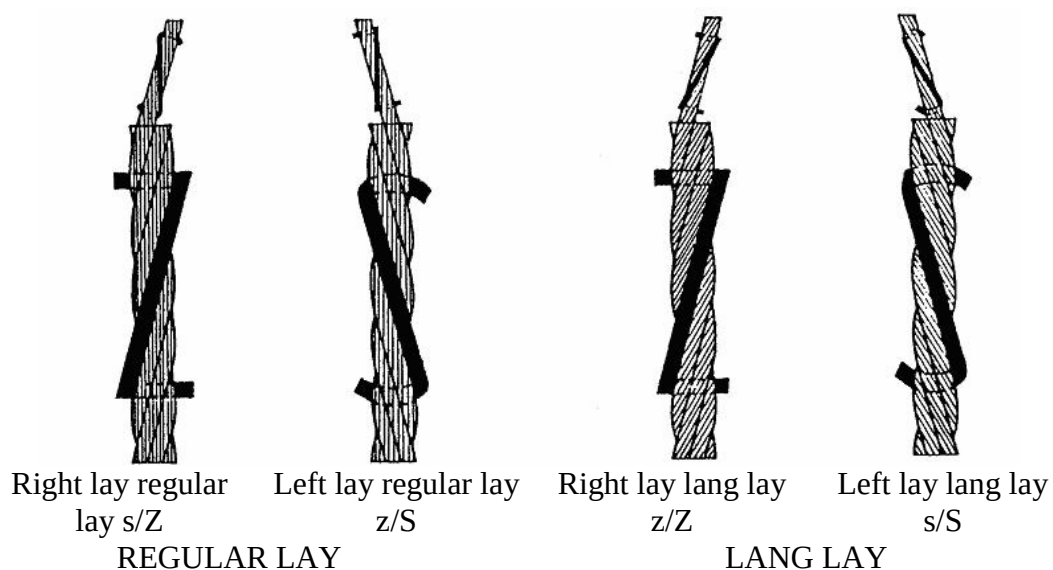


Figure 2.12 : Rope lay (BS 6570, 1986).

2.2.4 Wire Grade

The most common steel wire grades are: 1420-1770 N/mm², and 1860N/mm². Stainless steels and other special grades are provided for special applications. Most wire ropes are made with round wires. Both triangular and shaped wires are also used for special compositions. Generally, the higher the strength of the wire, the lower it's ductility will be (Cookes Limited, 2007).

2.2.5 Wire Rope Size

Wire rope is described principally by its diameter and composition. It is therefore appropriate that these two items are the first discussed before going into a more detail about the wire rope or how to correctly describe it. There is only one correct method of measuring the diameter of a wire rope, this should always be followed to prevent errors or misunderstandings. The method is shown below. The size of a wire rope is the diameter of a circle, which will just enclose all the strands (Figure 2.13).

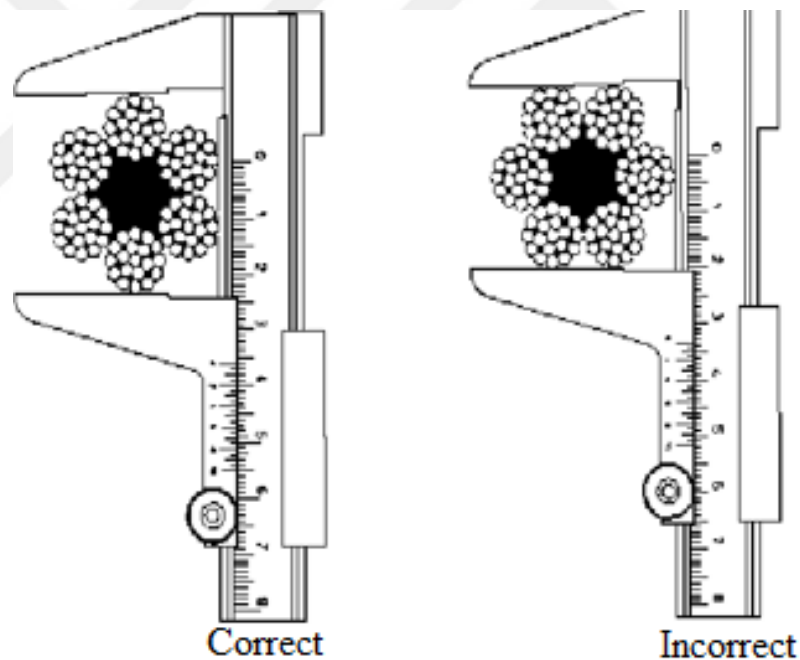


Figure 2.13 : Diameter of rope (Union, 2016).

Wire rope is usually described by its nominal diameter, which may vary slightly from the actual diameter. The amount of variation allowed varies depending on the standard the wire rope conforms to, and the diameter (Union, 2016). It can be seen from Table 2.1.

Table 2.1 : Variation amount the diameter.

Nominal diameter in mm	Permissible deviation from nominal diameter in % accepted by manufacturers	
	Ropes with	
	Strands exclusively of steel wires	Strands with fibre cores
2 and 3	+7.-1	+9.-1
4 and 5	+6.-1	+8.-1
6 and 7	+5.-1	+7.-1
8 and over	+4.-1	+6.-1

2.2.6 Preforme ropes

In the rope manufacturing, the constituent elements that are wires and strands are pre-shaped helically before they assembled in the finished rope. With this operation, natural tendency of the wires and strands removed, and it provides to keep their proper position. Preformed wire ropes can be cut without the seizings necessary to keep the rope structure of non-preformed ropes. One of the important advantages of them, broken rope ends do not untwist as do the ends of the non-preformed ropes. This increases the salvage value of broken ropes. They are fundamentally free from twisting tendencies and liveliness. This makes installation and handling easier, and lessens the likelihood of damage to the rope from kinking or fouling. Preforming allow the more general use of Lang lay and wire core compositions. Removal of internal stresses increase resistance to fatigue from bending. This results in increased service where ability to withstand bending is the important requirement. It also allows the use of ropes with larger outer wires, when increased wear resistance desired. Outer wires will wear thinner before breaking, and broken wire ends will not protrude from the rope to injure worker's hands, to nick and distort adjacent wires, or to wear sheaves and drums. Because of the fact that broken wire ends do not porcupine, they are not as noticeable as they are in non-preformed ropes. This necessitates the use of greater care when inspecting worn preformed ropes, to determine their true condition (Cürgül, 1995).

2.3 Lubrication

The wire rope lubricant has two major tasks: it should protect the rope from corrosion and it should minimize the friction between the rope elements themselves and between the rope and the sheave or the drum. A reduction of the friction reduces the actuating power and minimizes the wear of the rope, the sheaves and the drums. Some manufacturers apply the lubricant at the time of final assembly of the strands into the finished wire rope, while others have sophisticated equipment which will apply it the individual wires, and then again to the individual strands.

The method of application and the selection of the lubricant have a considerable effect on the service life of a wire rope. In addition to reducing wear, the lubricant aids prevent internal and external corrosion. This is more important on bright steel wires than galvanized wires, so usually a different lubricant is used on galvanized wires. In most cases, wire ropes are lubricated intensively during the production process. Nevertheless, this initial lubrication has to be renewed regularly during the whole rope's lifetime. A regular re-lubrication contributes to an increase in the rope's service life. The lubricant used for re-lubrication needs to be compatible with the lubricant used during production. Different operating conditions may require specialized lubricants, and most manufacturers can accommodate this requirement. Attention to lubrication of a wire rope during its service life can give a considerable increase in that life (Feyrer, 2007).

2.4 Materials

Everlastingly, good wire rope is dependent as much on the quality and consistency of the raw material wire as it on the composition and assembly of the finished product. The chemical contents of the wire, and its mechanical properties such as breaking load, bending characteristics, and torsion are all tested by the manufacturer to provide that each batch exceeds minimum requirements. It is also important that these tests give consistent values. This consistency contributes to the service life of the finished wire rope.

Bright steel wire is generally used for making wire ropes which used in areas where corrosion and rust is not an important problem. However, a well chose lubricant can have almost as much benefit in reducing corrosion in bright steel wires as it can in reducing wear.

Galvanized steel wire offers better protection than a lubricant in more corrosive atmospheres. Tests have also shown that bright steel wire rope used in hoisting applications often has a significantly shorter life than galvanized wire rope, even though there is no corrosive element present. This seems to be due to a reduction in contact stresses due to the zinc coating. Although this effect is similar to that of a lubricant, sufficient lubrication is still needed.

Galvanized wires are tested by the manufacturers as with bright steel wires, before being used for rope making. Besides, tests for uniformity and adhesion of the zinc coating are carried out to ensure they meet acceptable standards. Test certificates for wire rope often show the weight of zinc on a wire in grams per square meter.

Wire ropes made from stainless steel wire are extremely resistant to corrosion, even in very high temperatures. Until recently, only A.I.S.I types 302 and 304 were used for rope making, but today A.I.S.I. type 316 is common. This grade may have poorer mechanical properties however, has a much higher resistance to corrosion. Despite the higher initial cost, stainless steel ropes are being used increasingly particularly in marine environments and in areas where maintaining appearance is as important as preventing corrosion (Demirsoy, 1991).

2.5 Strand Compositions

In fact, only cross laid composition with wires of same diameter were used. Nowadays we generally use so-called parallel compositions, such as Warrington, Seale, and Filler Wire, and various combinations of these. It is also possible to have strands with fibre cores.

2.5.1 Cross laid composition

A strand of a wire rope in this composition consists of a number of wires, which have same diameter, laid together in several layers. The other important feature of this type of composition is that each layer in a strand has 6 more wires than the previous layer. The second layer has 6 wires laid around a center wire, the third, 12, and the fourth 18 etc. (Figure 2.14).

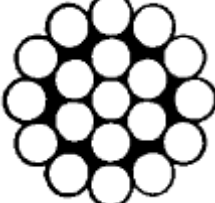
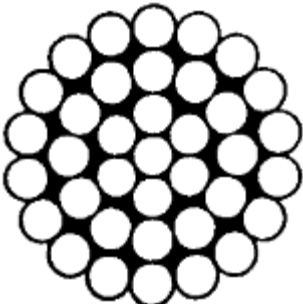
			
1 wire	+ 6 wires	+ 12 wires	+ 18 wires

Figure 2.14 : Cross laid composition.

This type of composition came about because of an original misconception that 6 wires of the same size would fit easily around a 7th wire of the same size. This takes no account of the fact that the cross sectional shape of the cut wire, after it has been wound into a rope, is not round.

It is necessary to lay the wires in the successive layers with the same lay angle, in order that all wires take an equal share of the load. The same angle of lay results in a different lay length in each layer, and the wires do not run parallel, but cross each other, hence the term "cross-laid".

When the wire rope is new, the contact areas between the wires of different layers are tiny. Wear will occur at these tiny points, and the contact points become notches when the wire rope is in operation. As wear continues, the notches will get deeper, and eventually the wires will no longer be able to slide along each other. When this point is reached, the rope can only be bent by actual stretching of the individual wires, finally causing their breakage.

Secondary breakage also occurs in those areas where the wires are not supported, i.e. between the points of contact where the wires cross each other. The wires of the outer layer will strongly compress the layer underneath when the rope bends around a sheave, due to the pressure between the rope and the sheave. Where the outer wires are not supported, the inward forces will slightly bend these wires. This secondary bending causes the material to be overloaded and fatigue of the wires often occurs with very little visible signs of wear of the rope (Figure 2.15).

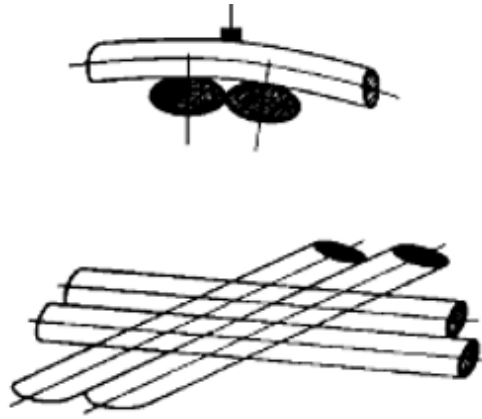


Figure 2.15 : Contact point between wires on cross laid composition.

It is not surprising, given these facts, that attempts have been made to find better rope compositions, and these have been found in the "parallel lay" compositions. Cross laid rope compositions are still manufactured due to their lower cost, but their main value is in slinging, or where a long life is not expected (Figure 2.16).

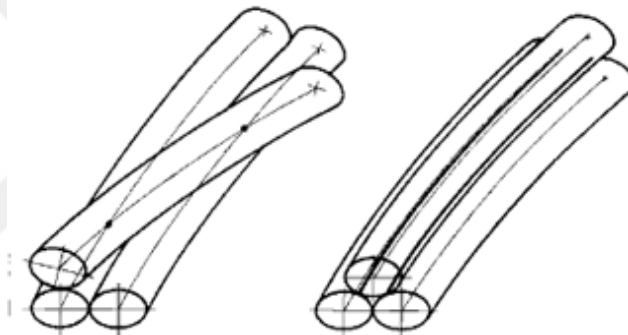


Figure 2.16 : Contact area between wires on paralel lay composition.

2.5.2 Composition with fibre cored strand

For some ropes, the significant requirement is very often high degree of flexibility while the breaking load is of secondary importance. The required flexibility is achieved by using fibre cores in the strands. Naturally, these ropes have a low resistance to degradation. Ropes with fibre cores in the strands should not be used as hoisting ropes as they have very little reserve strength, and they will flatten out very badly when bending over a sheave or onto a drum, which causes an irregular distribution of loads on the wires (Figure 2.17).

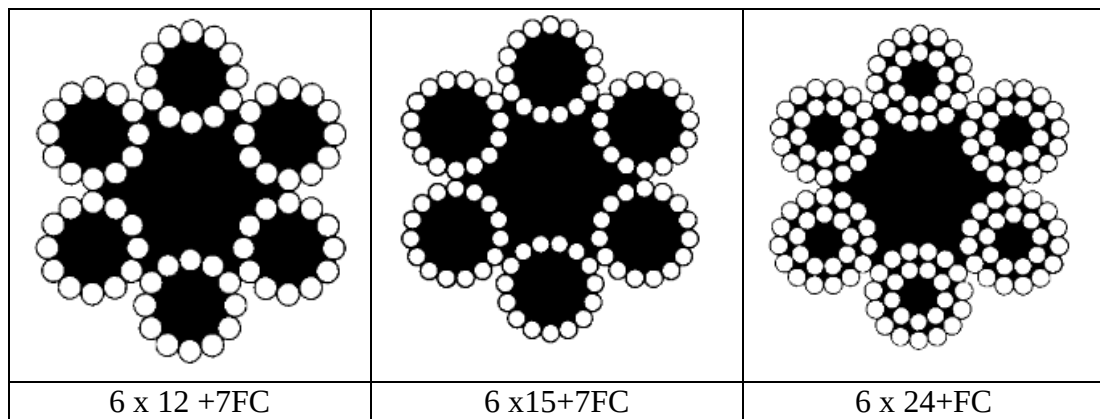


Figure 2.17 : Composition with fibre cored strand.

2.5.3 Paralel or equal lay composition

The parallel compositions are a remarkable improvement over the one-size wire cross laid compositions, and the difference in lay length in successive layers does not occur. In parallel compositions, the wires do not cross each other, but are laid parallel to each other; they all have the same pitch, and each subsequent layer lies in the grooves, or on the crowns of the wires in the layer below it (Figure 2.18).



Figure 2.18 : Paralel composition.

This arrangement of wires has many advantages. Due to the line contact of the parallel wires (instead of point contact between crossing wires), the wires can more easily slide along each other when the rope is bent. Due to this absence of crossings, no nicks or secondary bending will occur. Because of this, it is possible to use a shorter lay length without creating higher internal stresses, as you would with a cross-laid composition. The beneficial effect that this creates is that the cross sectional area of a cut wire rope will show wires have a more elliptical shape, which brings a bigger cross sectional area of wire into contact with sheaves and drums, and so gives the wire rope greater wear by lowering the surface pressure. The total cross sectional area of steel in a parallel laid wire rope is greater than in a cross-laid rope. They have a higher fill factor. There are fewer air gaps.

Consequently, a parallel composition wire rope can have a higher breaking load than a cross-laid wire rope of the same tensile strength and diameter. Alternatively, under the same load conditions, the safety factor is higher.

The difference between calculated breaking load (the sum of the tensile strength of the wires used) and the actual breaking load (which is effected by bending the wires into the rope) is smaller with a parallel laid rope. The smaller pressure between wires and smaller stresses in the wires, increases the flexibility, and makes it possible to use a rope with thicker outer wires on a given sheave than would be possible with a cross-laid rope. Additionally, parallel composition wire rope has better resistance to crushing because the outer wires are firmly embedded in the grooves of the wires in the layer below. Service life is longer because thicker outer wires give more resistance to wear and corrosion. Also, parallel laid compositions preform more easily during production, so consistency and quality are improved. The parallel compositions include amongst others the following:

- Seale
- Warrington
- Warrington Seale
- Filler wire/Seale, and Seale/Filler wire

2.5.3.1 Seale composition

Seale compositions have two key characteristics. All layers in a strand contain the same number of wires; e.g. in the most common Seale composition, 6 x 19 wire Seale, the strands are built up of a centre wire plus a layer of 9 wires, plus a second layer of 9 wires. The wires from the outer layers are embedded in the grooves created by the wires of the inner layers (Figure 2.19).

All the wires in a layer are of the same diameter, but the wires in the outer layer are thicker than those in the inner layer. The small number of relatively thick wires in the outer layer of each strand increases the resistance to crushing and to deterioration from wear and corrosion. However, the smaller number of thicker wires makes the rope less flexible than a rope with many thin wires therefore the rope has less resistance to bending fatigue. As a summary, a Seale composition rope has a low resistance to bending fatigue, but a high resistance to wear and corrosion.

The inventor of this rope composition achieved a considerable improvement over the one-size wire cross-laid compositions, and Seale composition is in common use today in many applications.

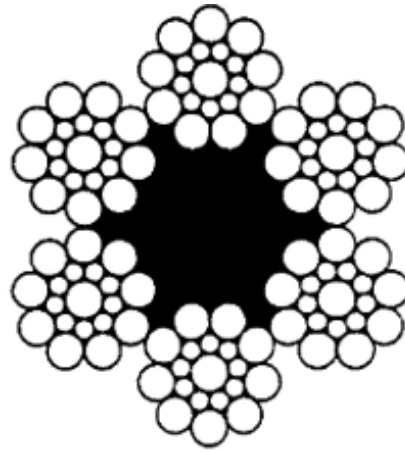


Figure 2.19 : 6 x 19 Seale + Fibre core.

2.5.3.2 Warrington compositions

Warrington compositions are most commonly found in mixed (e.g. Warrington Seale) compositions. The Warrington layer of the construction has twice the number of wires as the layer underneath it. Half of the layer is thicker wires embedded in the grooves of the layer beneath, and the other half is thinner wires which alternate with the thicker wires and sit on the crowns of the wires below. Hence, the wires are not all of the same diameter.

With the 6 x 19 Warrington compositions, for instance, the strands consist of a centre wire around which is laid one layer of 6 wires. Around this is a second layer of 12 wires, 6 wires lying in the grooves formed by the first layer and alternating with 6 thinner wires; all of these 12 wires touch the circumscribed circle of the strand (Figure 2.20).

The Warrington composition has many of the advantages of the Seale composition, but its smaller outer wires have less resistance to wear. However, it is more flexible, and therefore has more resistance to bending fatigue.

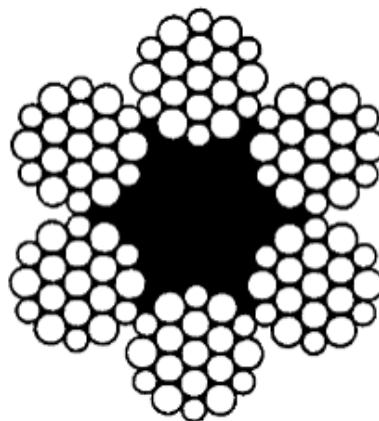


Figure 2.20 : 6 x 19 Warrington + fibre core.

2.5.3.3 Filler wire composition

In the Filler Wire compositions, the spaces between the layers of wires are filled up with thin wires, making for a larger cross sectional area of metal than with crosslaid compositions. Besides, the outer wires are supported over their full length so that this type of rope is more resistant to internal wear and deterioration than a comparable cross-laid rope (Figure 2.21).

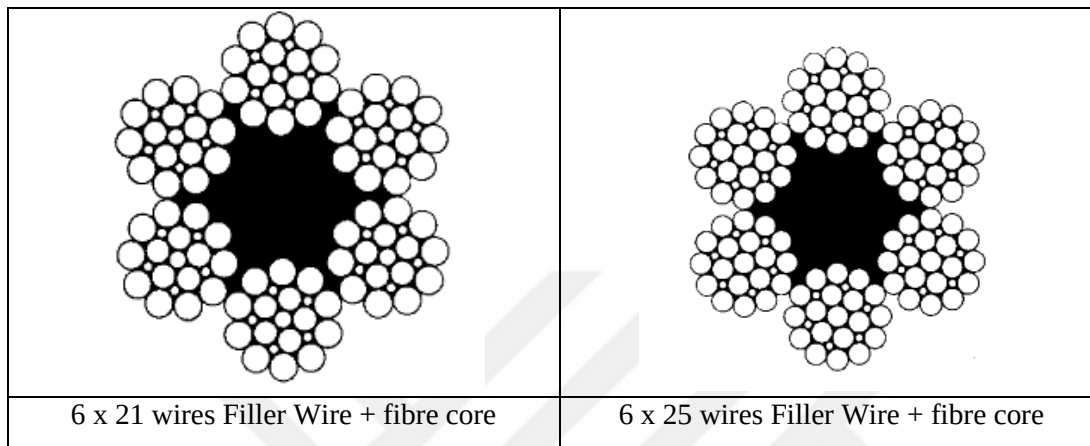


Figure 2.21 : Filler wire compositions.

It is the function of the filler wires to support the outer wires. Until recently, the filler wires were not taken into account when calculating the breaking load of the rope. It has however been proved in practice that the filler wires do increase the breaking load, so they are now accounted for.

2.5.3.4 Warrington-Seale & Filler Wire Seale composition

The wires alternate, a large wire than a smaller wire, and the larger wire sits in the groove formed by the wires in the layer below, while the smaller wire next to it sits on the crown of the wire in the layer below. Beside, Seale layer (the outer layer) has the same number of wires as the Warrington layer below it, but they are much larger, and they all sit in the grooves formed by the Warrington layer. These compositions have largely took place the cross-laid 6 x 37 wires (18+12+6+1) in hoisting applications.

Note the similarity in the Warrington/Seale compositions to each other when written in the same format (Figure 2.22).

- $6 \times 26 = (10+5/5+5+1)$
- $6 \times 31 = (12+6/6+6+1)$
- $6 \times 36 = (14+7/7+7+1)$
- $6 \times 41 = (16+8/8+8+1)$

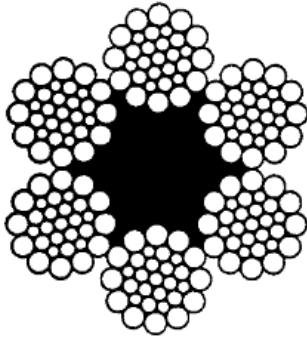
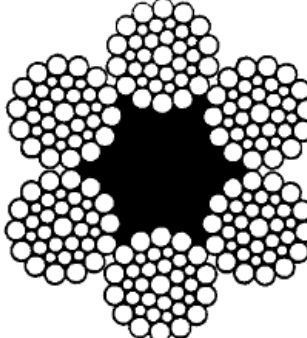
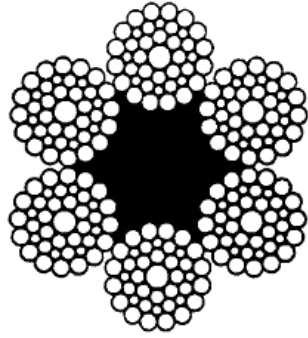
		
6 x 31 wires Warrington Seale +fibre core	6 x 36 wires Warrington Seale +fibre core	6 x 41 wires Warrington Seale +fibre core

Figure 2.22 : Warrington Seale & Filler Wire Seale composition.

It can be noticed that these ropes have the same number of outer wires as the equivalent Warrington/Seale composition, but some of the inner wires are much larger. These compositions could be written as follows;

$$6 \times 36 = (14+7F+7+7+1)$$

$$6 \times 41 = (16+8F+8+8+1)$$

These ropes have the Seale layer as the third layer, and have one more layer than a Warrington/Seale composition (the filler wire layer) (Figure 2.23).

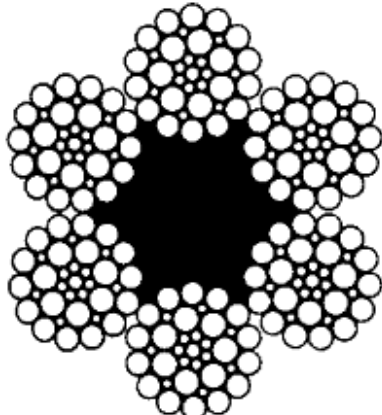
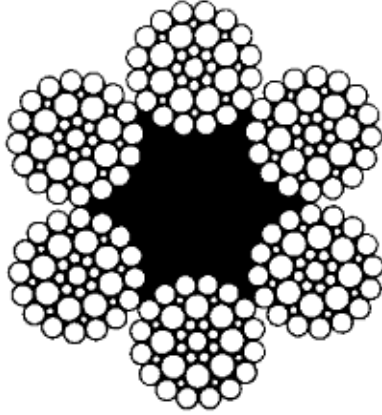
	
6 x 36 wires Seale/Filler Wire + fibre core	6 x 41 wires Seale/Filler Wire + fibre core

Figure 2.23 : Some typical combinations of Seale and Filler Wire composition.

2.5.4 The Number of Strands in a Wire Rope

Traditionally the majority of wire ropes are made up of 6 strands around a core. This tradition has probably grown from the original incorrect assumption that 6 strands fit exactly around a 7th strand of the same diameter, as with the composition 7 x 7, and 7 x 19.

More recently, ropes with a different number of strands have been used more successfully in some areas. Factors that influence this include;

- flexibility,
- the effect of radial bearing pressure,
- potential moment (the amount of tendency to untwist under load).

In any rope in which the strands and wires are laid in a helical pattern, a load will cause a moment (rotational force) which is related to the pitch circle diameters and lay angles.

There is a difference between the moments in the strands of the rope and those of the wires in the strand. These moments take effect in the same direction (Lang's lay) or in the opposite direction (regular lay). The magnitude of the moment is determined by the load absorbed per strand or wire (force) and the distance between the core of the strand and the core of the rope (distance).

2.5.4.1 3-Strand Composition

In 3 strand ropes the distance between the cores of the strands and the core of the rope is relatively small. By matching the length of lay of the strands in the rope to that of the wires in the strands it is (in theory) possible to achieve a moment equal to 0 without greatly reducing the breaking load. (The breaking load tends to be lower with a shorter lay length).

The major disadvantage with 3 strand rope is that it is not very round, so does not have good contact with sheaves and drums. For this reason, and because 3 strand lacks flexibility, sheaves and drums should be as large as possible.

Experts also recommend that no more than one layer be wound on a drum since the rope will wear badly by rubbing against itself. Newer forms of three strand rope have small filler strands which increase the roundness of the rope.

2.5.4.2 4-Strand Composition

In these compositions the distance between the cores of the strands and the core of the rope is larger than in three strand compositions, therefore the moment is greater, but it is much less than in traditional 6 strand compositions. When it is received in multiple parts, it is possible to allow twice the lifting height with 4 strand rope than with a 6 strand rope, when used under the same conditions. 4 strand ropes are considerably rounder than 3 strand. In many cases, it has been found that 4 strand ropes perform considerably better than 8 strand spin resistant wire ropes. It is generally safe to refer to 4 strand ropes as spin-resistant.

2.5.4.3 6-Strand Composition

As mentioned above, this composition is by far the most common and is, as it were, a good compromise between 4 strand composition, and 8 strand compositions with reduced spin, (which are more flexible and have much better resistance to higher radial bearing pressures).

2.5.4.4 8-Strand Composition

8 strand ropes are more flexible and have a much greater resistance to bending fatigue than a 6 strand rope of the same composition. Because of this greater flexibility, 8 strand ropes suffer less from reverse bending. They also wear better because they are much rounder, and therefore have a greater bearing surface. The smaller outer wire diameter will however give the rope less resistance to damage.

8 strand ropes are almost always made with a steel core. The reason of this is that the core is much larger than the strands, where in a six strand rope it is almost the same size. Because the soft fibre core fills a comparatively large space, it will crush down in size after a small amount of use, and leave the strands wearing against each other. The resulting wear would soon be serious, and the service life of the rope would be shortened considerably. A wire rope core provides permanent support for the strands, and it will suffer much less from shock loading.

To reduce the tendency to rotate, an 8 strand rope can be made with its core laid in the opposite direction. Because of the relatively large size of the core, this produces a rope with low rotation characteristics. The rope is not suitable for use on single part cranes however since any significant rotation would overload the core creating a potential for danger. Figure 2.24 illustrates 8 strand composition.

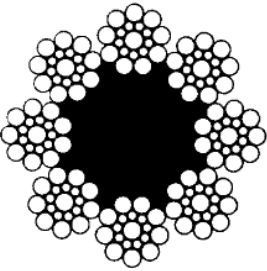
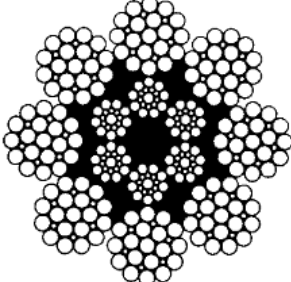
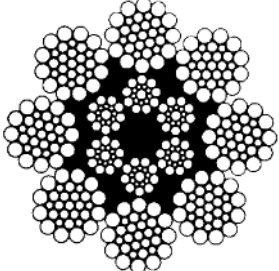
		
8 x 19 wires Seale+fibre core	8 x 25 wires Filler wire + IWRC	8 x 31 wires Warrington/Seale+ IWRC

Figure 2.24 : 8 strand composition.

2.5.5 Non Rotating Compositions

This term includes all ropes made up of two or more layers of strands round a fibre or wire rope core; the inner layer or layers having the reverse lay to the outer layer. The reduced tendency to rotate is not so much based on a low potential moment, as described for 3 and 4 strand ropes, so much as a rapid adjustment of equilibrium.

If these ropes are subjected to a load, the outer layer will untwist and lengthen. Simultaneously however, the inner layer or layers which are reverse laid will close up and shorten. The effect of this elongation (load reduction) and shortening (load increase) is a rapid change in the load distribution: the load effectively jumps from the outer layer to the inner layers. As soon as this happens, the inner layers will begin to untwist and lengthen, and the whole process is reversed.

To prevent overloading during this stage of reaching equilibrium, higher safety factors are often used for non-rotating compositions. Tests have shown that the breaking strains can be reduced by as much as 2/3, which will also reduce the safety factor. The more material proportionally in the inner layers, the sooner the stage of equilibrium is reached, and the sooner the load stops rotating, and consequently the risk of overloading is reduced.

Non-rotating compositions are being used more and more, but they do have a number of inherent disadvantages, which require the user to exercise care, and they are:

- When these ropes bend over a sheave, the reverse laid layers move in different directions. One layer will tend to open up while the other will tighten. Small sheaves and high loads increase this tendency. Rope damage can occur quickly from inter-wire and inter-strand friction if sheave diameters are too small.
- A similar problem to that mentioned above occurs on drums, but with the added complication that if a rope is left wound on a drum for any length of time a permanent difference in length can occur between the layers.
- Non-rotating compositions do not lend themselves well to pre-forming. This has the effect that the recovery rate of the rope from deformations is slower than for a normally well-preformed rope. The change in the ropes characteristics caused by the previously mentioned point above can result in bird-caging (the inner strands bulging through the outer).

- Because of the necessity to keep the inner layers and the outer layer in the same relative position, great care is required when fitting terminations. Fusing of the layers of the rope together at the ends is a technique commonly utilized. Allowing the layers to move in their relationship with each other can prevent equilibrium being reached with a load, and result in breakage of the rope. Figure 2.25 shows the non rotating compositions (TS EN 12385-2, 2005).

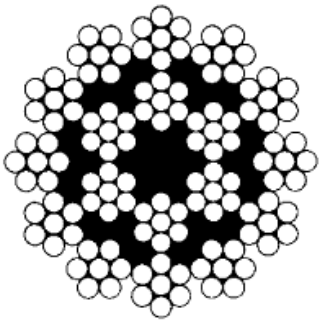
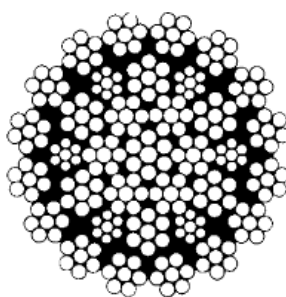
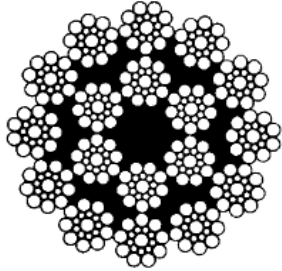
		
18 x 7 wires + fibre core	35 x 7 wires + fibre core	8 x 19 wires Seale + fibre core

Figure 2.25 : Non rotating compositions.

2.5.6 Wire ropes according to strand type

General purpose of steel wire ropes complying with BS 302 are basically of three types: round strand, triangular strand and multi-strand. All three types of rope are made with cores of either fibre or steel. Strand compositions are known by name and by numerical designation, e.g. 6×36 Warrington-Seale, or 6×36 (14/7 and 7/7/1) FC. This example explains a rope having six strands and a fibre core, each strand containing 36 wires, with the outer layer having 14 wires, the second layer seven large and seven smaller wires, the inner layer seven wires around one king wire.

2.5.6.1 Round strand ropes

The strands of round strand ropes are of two types, equal lay or cross lay. In equal lay strands, the wires in the outer layer lie either in the valleys between the wires of the inner layer or along the crowns of the underlying wires. In cross lay strands, the wires of the outer layer cross over the crowns of the underlying wires. For a given rope diameter and wire tensile grade, equal lay ropes have a higher breaking load, better bend fatigue performance and better resistance to crushing. For general purposes,

equal lay ropes have almost entirely take place cross lay ropes except in the smaller sizes. The equal lay round strand ropes specified in BS 302 have three basic strand compositions (TS EN 12385-2, 2005).

Seale: In this composition, the strands have two layers of wire around a king wire both layers having the same number of wires and the same length of lay (Figure 2.26.a).

Filler: In this composition, the strands have two layers of wires around a king wire, with twice as many wires in the outer layer as in the inner layer. Both layers have the same length of lay. Additional comparatively small wires (filler wires) are incorporated in the valleys of the six inner wires to support and correctly position the outer layer of wires. The filler composition is indicated in designation by the sign “+” (Figure 2.26.b).

Warrington-Seale: In this composition, the strands have three layers of wire around a king wire. In the 6×36 composition, for example, there are seven wires of equal size in the inner layer, 14 in the intermediate layer, being alternately large and small (Warrington layer) covered with 14 wires all of the same size (Seale layer). All three layers have the same length of lay. (Figure 2.26.c).

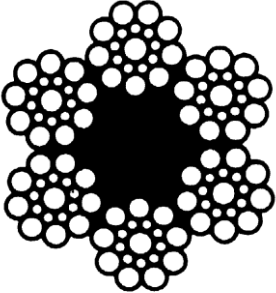
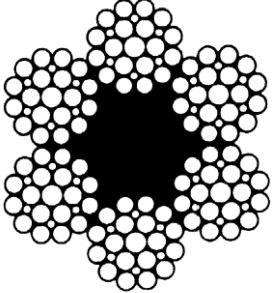
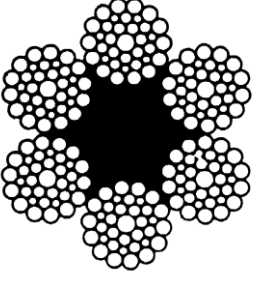
		
6 X 19 (9/9/1) fibre core	6 X 19F (12/6 + 6F/1) fibre core	
Typical Seale strand rope	Typical Filler wire rope	Typical Warrington-Seale strand rope

Figure 2.26 : Round strand ropes.

2.5.6.2 Triangular strand ropes

These ropes are built up from triangular strands and are of Lang’s lay composition. The wires forming the strands are laid on a triangular shaped core. The core is formed by a single triangular shaped wire or by using three or more round wires formed into a triangular shape (Figure 2.27). For composition notational purposes the latter are counted as one wire (TS EN 12385-2, 2005).

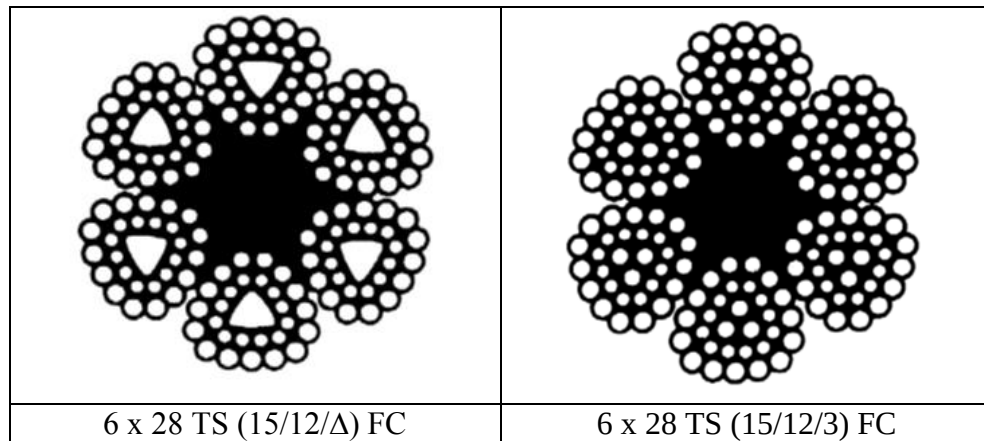


Figure 2.27 : Typical triangular strand rope.

2.5.6.3 Multi-strand ropes

This type of rope has two or more layers of strands, which are laid in opposite directions so that their rotational tendencies under load act in opposition. The type of lay in the outer and inner layers is at the discretion of the rope manufacturer. Although these ropes are referred to as non-rotating, low rotation, or anti-spinning, it should be recognized that these are relative terms, since all such compositions have some tendency to rotate under load. The preferred term is rotation resistant. Multi-strand ropes require greater than normal care when being handled, prior to, during and after installation. For advice when fitting multi-strand ropes (Figure 2.28)

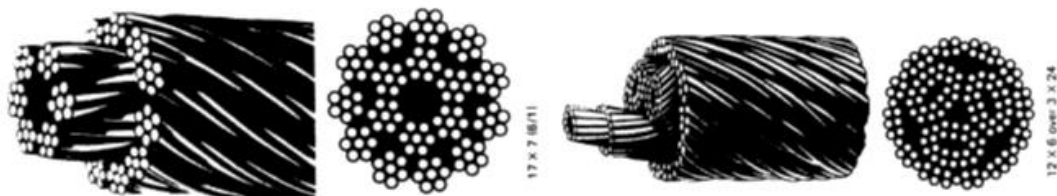


Figure 2.28 : Example of multi-strand rope (TS EN 12385-2, 2005).

2.6 Wire Rope Classification According to Application Area

The wire ropes used in a wide application area. It is explained which type of compositions and properties are preferred for some important area as follows.

2.6.1 Crane ropes

When choose a crane rope following parameters should be considered.

- Load capacity,
- Wear resistance,
- Fatigue resistance,

- Rotation resistance,
- Corrosion resistance.

Commonly used rope composition for the Crane applications are as follows. 18 x 7 Fiber core, rotation resistant rope, 6 x 36 Warrington Seale Fiber core rope commonly used for ships or sand crane. Especially for the shipment wear and impact resistance are very important. When these properties are more important to corrosion resistance 6 x 25 Fiber core black (not galvanized) ropes can be used as well. It is observed that the 6 x 36 Warrington Seale fiber core (galvanized) rope give good results.

2.6.2 Chair lift

When choose a rope for chair lift following parameters should be considered.

- Wear resistance,
- Fatigue resistance,
- Corrosion resistance,
- Technical safety rules.

Commonly preferred rope compositions for chair lift are 6 x 7, 6 x 13 or 6 x 19 Seale type with same wire and strand directions. It can be produced with fiber core, galvanized or black wire according to customer needs. If the rope is not galvanized it must be lubricate.

2.6.3 Marine ropes

These rope works in corrosive environment therefore it should have following properties.

- Corrosion resistance in salty environment,
- Fatigue resistance,
- Easiness of use,
- Load capacity.

Commonly preferred marine ropes compositions are 6 x 7, 6 x 19, 6 x 24, and 6 x 37 with steel core or polypropylene core. Marine rope always manufactured as galvanized and without lubrication. Lubrication or grease, which will use for the marine rope, should be appropriate for the corrosive environment.

2.6.4 Mining rope

These rope uses for the heavy service, so its properties should be as follows:

- Loading capacity,
- Fatigue resistance,
- Impact resistance,
- Wear resistance,
- Bending strength,
- Corrosion resistance.

Commonly preferred mining rope compositions are 6 x 19 Seale, 6 x 36 Warrington-Seale, 6 x 25 Filler and 6 x 41 Warrington-Seale steel core. Their wires in the strands has to be in same pitch parallel lay.

2.6.5 Elevator ropes

These ropes usually use for carrying people, so its properties should be as follows:

- Fatigue resistance,
- Wear resistance,
- Impact resistance,
- Appropriate preform properties.

Commonly preferred rope for these purpose, has fiber core, Seale or Filler composition and parallel wire same pitch. For instance 6 x 19 Seale, 6 x 25 Filler, 8 x 19 Seale compositions are used. Due to their flexibility and thicker outer wires they have good resistance against to wear. It is recommended that the wire rope safety factor has to be at least 12 for the elevator used for human transportation purpose.

2.6.6 Fishery rope

Fishery rope works in corrosive environment so its properties should have as follows:

- Resistance to seawater,
- Resistance to high stress,
- Easiness of use,

- Wear resistance.

As a fishery rope, 6 x 7 Standard, 6 x 19 Seale, 6 x 24 compositions with polypropylene core ropes commonly used. For the corrosion resistance the rope coated with zinc.



3. FACTORS EFFECTING WIRE ROPE LIFETIME

The objectives of this chapter are to review factors which affect wire rope life, and propose a simulation method for choosing a design factor which incorporates economics of the hauling system. The simulation method for determining design factors will only consider static tensions. Static tensions involve forces which are not due to changes in velocity as the log is being yarded. Dynamic tensions, which include positive or negative changes in velocity, will not be considered in the simulation method. Hang-ups, log breakout, and logs swinging free of the ground (in transition from partial to full log suspension) are considered examples of dynamic loads (Demirsoy, 1991).

The main factors affecting rope life are, the elastic limit, tensions caused by static and dynamic loads, rope composition, axial stresses, bending stresses, bending fatigue, rope maintenance, lubrication, corrosion, line use, and line length.

3.1 Tensile Load

To associate the tensile load and fatigue life Feyrer (2007), has performed several experiments on wire rope which has following properties. The rope has 30 mm in diameter, 1770 N/mm² yield strength, exposed to 40 kN tensile load. In case of using sheave 600 mm in diameter, he observed that the rope reach to the discard criteria with 400000 cycles and it reach the breaking point with 900000 cycles. Thus, he obtained graph that represent the relation between tensile load and bending fatigue life (Figure 3.1). Lower curve is derived according to the rope reach to the discard criteria, whereas upper curve is derived according to the rope reach to the breaking point. With respect to the obtained results, it can be concluded, when the tensile load increases bending lifetime decreases.

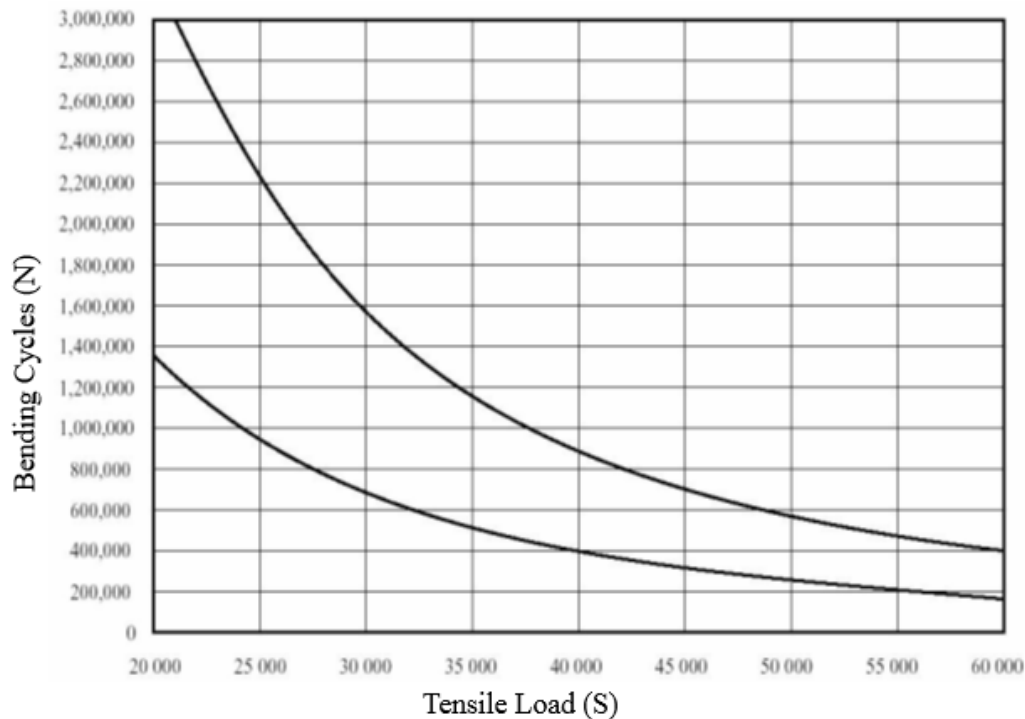


Figure 3.1 : Bending fatigue life changes in different tensile load (Verreet, 1998).

3.2 Effect of Sheave Size

Sheave diameter is one of the important parameter that effect the rope strength. When a wire rope is bent around a sheave, there is a loss of effective strength. This is due to the inability of the individual strands and wires to adjust themselves entirely to their changed position. Tests prove that rope strength efficiency decreases to a marked degree as the sheave diameter is reduced with respect to the diameter of the rope. Therefore, it is evident that a definite relationship exists between rope service and sheave size. As a guide to rope users, wire rope manufacturers have established standards for sheave sizes to be used with various rope compositions (Feyrer, 2007). Figure 3.2 shows the effects of tensile load and diameter ratio on bending fatigue lifetime on the same graph. Experiments are conducted to 8 x 25 Filler ropes with 16 mm in diameter, and 1650 N/mm² yield strength. It can be seen from the graph when the diameter ratio decreases, bending lifetime of a wire rope decreases as well. It is important to use compatible sheave deameter for the load to be lifted. For instance, using the sheave which diameter ratio $D/d = 10$, specific load cannot be more than 200N/mm². As it can be seen from graph, in these cases lifetime of a wire rope reduce dramatically. This load named as Donandt Load.

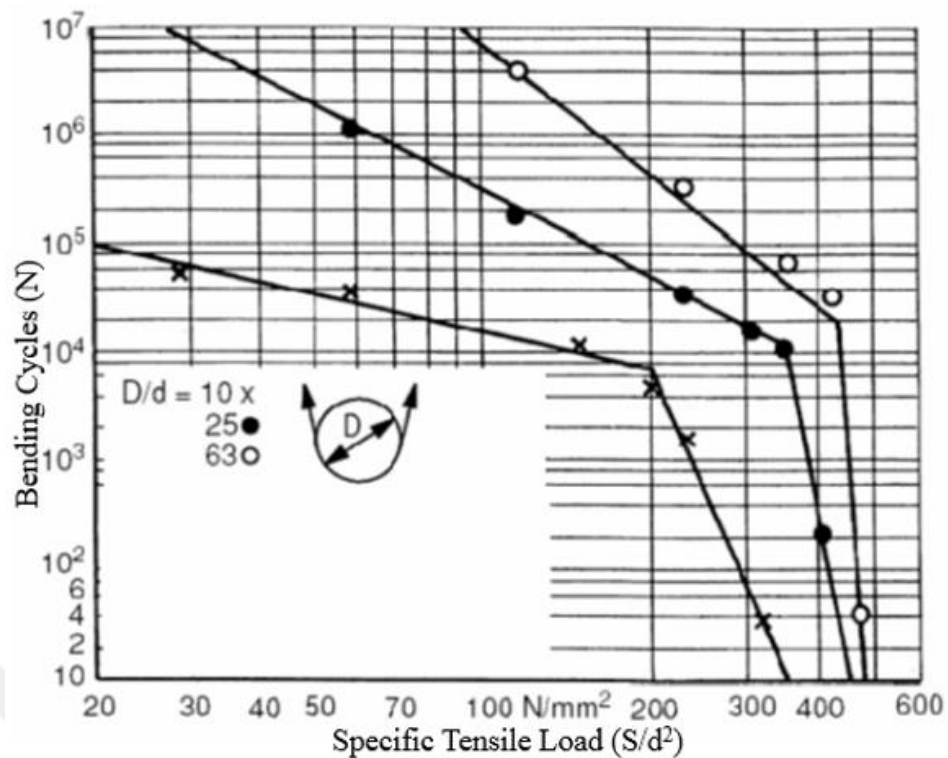


Figure 3.2 : Life of 8 x 25 Filler wire rope according to tensile load and diameter ratio (Feyrer, 2007).

3.3 Bending

Wire ropes are generally exposed to unnecessary bending fatigue. For instance, when one compares the fatigue lifetime of the same system with different crane block as in Figure 3.3.a has two small sheaves, and it causes the wire rope is bending two times for each hoisting, whereas Figure 3.3.b has one big sheave and the wire rope is bending only once. Instead of using two small sheaves, one sheaves with relatively bigger diameter provides better resistance to bending fatigue. Not only, because of the number of sheave used in the applications, but also the sheave has bigger diameter. As it mentioned in previous chapter when diameter ratio D/d increases bending fatigue life of a rope increases (Verreet, 2002).

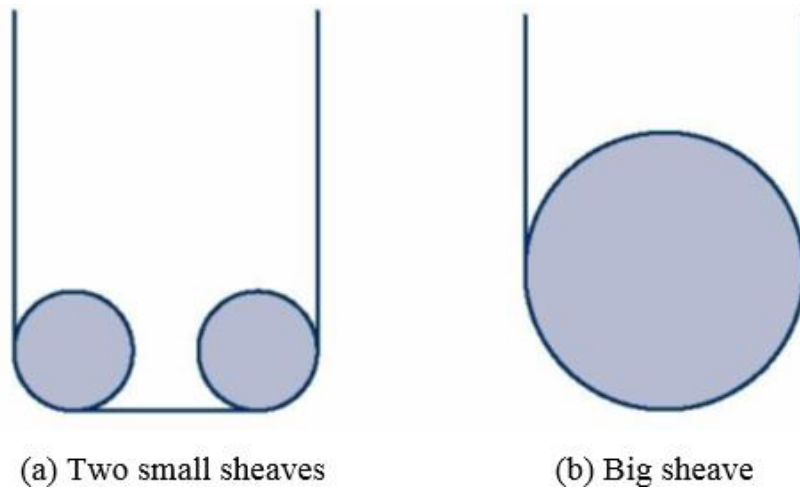


Figure 3.3 : Two types of Crane block (Verreet, 2002).

Additionally, when the wire rope subjected to reverse bending causes 2 or 7 times less fatigue life than the wire rope subjected to simple bending. Figure 3.4a 3.4b show the wire rope subjected to simple, and reverse bending respectively. As a result, the lifetime of a wire rope, which is subjected to reverse bending can be increase by increasing the sheave diameter or decreasing the tensile load (Verreet, 2002).

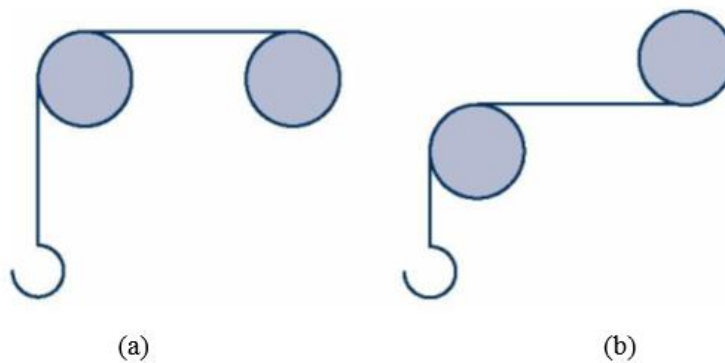


Figure 3.4 : Simple (a) reverse (b) bending (Verreet, 2002).

3.4 Elastic Stretch

Within limits, wire rope can be thought of acting like a linear spring. The range in which the rope will act like a linear spring has an upper limit known as the elastic limit. Within the elastic range (the elastic limit), wire rope can be stretched under tension and then returned to its original length and diameter when the tension is removed. The elastic stretch of a rope can be calculated from the expression (equation 3.1) (BS 6570, 1986).

$$Stretch = \frac{WL}{AE} \quad (3.1)$$

where:

W = load on the rope (kg)

L = rope length (m)

A = actual metallic cross sectional rope area (mm²)

E = modulus of elasticity of the rope (kg/mm²)

However, since the value of A and E for rope are not generally published it is convenient to use the overall rope area for A, based on equation 3.2

$$A = \frac{\pi d^2}{4} \quad (3.2)$$

where d is equal the nominal rope diameter and to use the following values for E:

- 6-strand ropes, fibre core: 58.8 kN/mm²
- 6-strand ropes, IWRC: 64.7 kN/mm²
- multi-strand ropes: 53.9 kN/mm²

3.5 Wire Grade

When the strength of the wire increases from 1370 N/mm² to 1570 N/mm² the wire rope computational safety increase greatly but fatigue lifetime increase very slightly. When it increases more (from 1570 N/mm² to 1770 N/mm²) the computational safety increases more. However, with higher strength of wire (1960 N/mm²) the lifetime of the wire rope decreases (Ernst, 1973).

3.6 Shape of Sheave Groove

Wire ropes are manufactured in a great variety of compositions to meet the varying demands of wire rope usage. Where abrasion is an important factor, the rope must be made of a coarse composition containing relatively large wires. In other cases, the great amount of bending to which a rope is subjected is more important. Here, a more flexible composition, containing many relatively small wires, is required. In either case, however, if the rope operates over inadequate size sheaves, the severe bending stresses imposed will cause the wires to break from fatigue, even though actual wear is slight. The smaller the diameter of the sheave, the sooner these fatigue breaks will occur and the shorter rope life becomes. Another undesirable effect of small sheaves is accelerated wear of both rope and sheave groove. The pressure per unit of rope on sheave for a given load is inversely proportional to the size of the sheave. Another

words the smaller the sheave the greater the rope pressure per unit area on the groove. Using the proper diameter sheave for the size and composition of rope can obviously prolong both sheave and rope life.

As a rope is run through a groove, both become smaller. A used groove can be too small for a new rope, thus accelerating rope wear. A compromise between rope life and machining frequency must be made. Grooves should have an arc of contact with the wire rope between 135 and 150 degrees. They should be tapered to permit the rope to enter and leave the groove smoothly. Field inspection groove gauges are made to the nominal diameter of the rope plus 1/2 of the allowable rope oversize tolerance.

3.7 Material of Sheave Groove

Usually shaves and drums are manufactured from steel or cast iron. In some cases, steel groove materials should be tampered this increase the bending fatigue lifetime of the wire rope. The reason of this, is the prevented the changes of groove geometry due to wear (Feyrer, 2007).

3.8 Diameter of Wire Rope

With the increases of the wire rope diameter, the lifetime of a wire rope increases for a while, but after the maximum value it starts to decrease. Figure 3.5 shows the experimental results for the specific wire rope in order to explain relation between diameter of wire rope and fatigue endurance. Upper curve is drawn considering the wire rope subject to bending until it is broken, and lower curve is drawn considering the discard criteria.

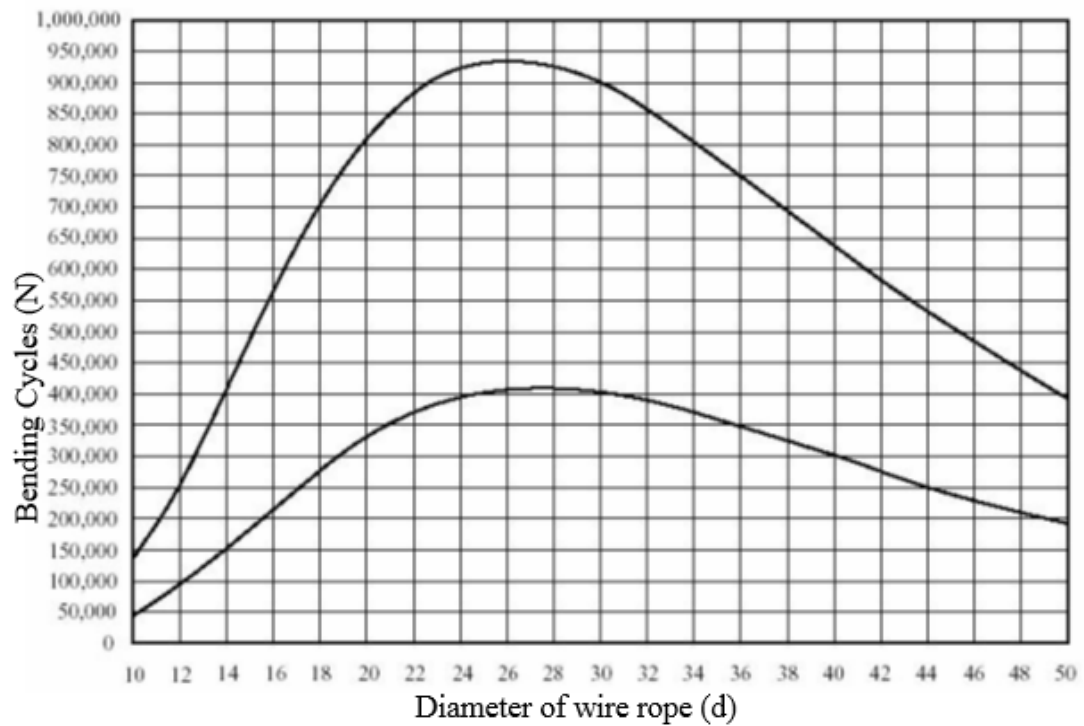


Figure 3.5 : Life of the rope with different diameter (Verreet, 1998).

3.9 Wire Thickness

Theoretical bending stress occurring in the wire rope wrapped around the drum or sheave can be calculated by equation 3.3:

$$\sigma = \frac{\delta E}{D} \quad (3.3)$$

where;

δ : Diameter of wire,

D: Sheave diameter

E: Young's module of wire materials.

However experiments proves that the wire rope with thicker wires is more suitable than wire ropes with thinner wires when they use in the same diameter of shave. The reason of this, thinner wires are more sensitive than thicker wires against to pressure on the sheave. The groove diameter increse i.e. the contact between wire rope and sheave getting worse, the advantages of thicker wires can be seen obviously (Cürgül, 1995; Ernst, 1973)

3.10 Rope Composition

Bending fatigue and abrasive wear are two major destructive forces on wire rope. The type of rope composition greatly determines the degree to which the rope will resist these destructive forces. In most cases, selecting a suitable wire rope which will resist all the destructive forces equally well is not feasible. For example, a rope which has relatively few outside wires is highly resistant to abrasive wear, but is markedly less resistant to bending fatigue because of the resulting increased stiffness associated with fewer outside wires. For these reason a compromise must usually be made in the design and application of a wire rope for any specific operation. Most wire ropes used in cable logging are in the 6 x 19 class (6 strands with 9 to 26 individual wires per strand) with an independent wire rope core (IWRC) and reflect this compromise. Ropes in the 6 x 19 class are resistant to abrasive wear, but less resistant to bending fatigue than ropes in the 6 x 26 class because of the greater stiffness of individual wires in 6 x 19 wire rope (Ernst, 1973).

3.11 Types of Tension

Wire rope tensions can be divided into two types:

- 1) static,
- 2) dynamic.

Static tensions involve forces, which are not due to changes in velocity as the log is being yarded. Dynamic tensions involve positive or negative changes in velocity. Hang-ups, log breakout, and logs swinging free of the ground (in transition from partial to full log suspension) are considered examples of dynamic loads. Breakout forces are the forces required to overcome log inertia. Design factors include both of these tension types, either explicitly or implicitly. Static tensions are explicitly calculated by payload analysis techniques. Dynamic tensions have not commonly been explicitly included in the analysis of wire rope tensions due to their variable and unpredictable nature. The design factor is usually increased to include allowances for dynamic tensions.

3.12 Axial Stress

Axial or normal stresses are created by forces directed along the axis of the rope. Axial stress is equal to the ratio of the tension in the wire rope to the actual metallic area of the wire rope (equation 3.4). The breaking strength of wire rope is determined by its tensile strength.

$$f_a = T/A \quad (3.4)$$

where:

f_a = axial stress (MPa)

T = the tension in rope (N)

A = actual metallic cross sectional rope area (mm²)

3.13 Lubrication and Relubrication

Lubrication protects the wires of the rope against corrosion and minimizes external and internal wear. However, lubricating wire ropes is a difficult issue, regardless of the composition and composition. Ropes with fiber cores are somewhat easier to lubricate than those made exclusively from steel materials. For this reason, it is important to carefully consider the issue of field relubrication when selecting rope for an application.

Wire rope lubricants have two principal functions, one of them to reduce friction as the individual wires move over each other, the other to provide corrosion protection and lubrication in the core and inside wires and on the exterior surfaces. To provide this protection, specific characteristics a lubricant must have as following:

- Have good covering properties
- Be water-repellent, water-resistant, and not emulsifiable
- Not be subject to significant embrittlement
- Not have grit, abrasives, water, chlorine, or similar impurities
- Not contain additives or compounds, which can form corrosive products caused by water contamination or additive degradation
- Must be able to penetrate into the core of the wire rope.

Wire ropes are initially lubricated during manufacturing. This lubrication protects the rope from corrosion during transportation and storage and reduces friction and wear

during its initial use. However, the initial lubricant does not last. Relubrication is required because the lubricant works out of the rope or dries out after a certain period of use. To obtain maximum service life, ropes should be relubricated at regular intervals. These intervals are dictated by various factors, such as the type of lubricant used, rope storage conditions, and method and frequency of use. There are several techniques for relubrication; the most common are “painting” and “swabbing.” These techniques, however, rarely penetrate the lubricant down to the core of the rope. Using a high-pressure lubricator is preferred, because it provides good penetration of the lubricant into the rope. The degree of penetration achievable with any technique also depends on the type of lubricant used. (Verreet, 2004; Turner & Barnes, 2002).

3.14 Corrosion

Corrosion, often in combination with fatigue, is a main cause of wire rope deterioration in service. Except under very dry conditions there is always some corrosion of unprotected (bright) steel wires. In some respects, the requirements for corrosion resistance and fatigue resistance are opposed. For the former, a small number of large wires is an advantage, whereas for the latter a large number of small wires is to be preferred. Choice of composition is, therefore, nearly always a compromise. To inhibit the onset of corrosion, ropes should be given frequent applications of suitable dressings during their working life. If there is a risk of severe corrosion, it is preferable to use a rope with galvanized wires (BS 6570, 1986).

3.15 Drum Winding

It is very important to have a rope wind evenly and tightly on a smooth drum. In consequence of lay direction and tension, rope has a tendency to rotate or roll as it approaches a winch drum. This characteristic is used to advantage by establishing the winding direction and dead end location so the rope will rotate in the direction of the preceding wrap. Tightly packed wraps on the all-important first layer will ensure proper winding for additional layers.

If the drum attachment and direction of wraps are not correctly selected, the first layer of rope will not wind evenly or tightly, causing the second layer to pinch down between the wraps of the first layer. The resultant unbalanced winding will become worse with each succeeding layer and result in abnormal scuffing and abrasion. If there are

sufficient layers the rope will pile up and “fall over” on itself with disastrous results. The hand rule is an appropriate way to check the correct lay for an installation. The extended thumb points to the flange to which the rope is terminated while the extended forefinger represents the rope leaving the drum. A palm up hand represents under wind and palm down overwind. If the right hand meets the conditions, use right hand lay rope and vice versa (Feyrer, 2007).

3.16 Fleet Angle

Excessive fleet angles can cause serious damage to wire rope, sheaves and grooved drums. Severe scuffing results when rope wears against groove walls, grinding them down causing the rope to become bruised and crushed.

Fleet angles on equipment should preferably be kept between 1° and 1.5° and should not exceed 2° for smooth drums or 4° for grooved drums. To ensure the rope crossing back and starting the second layer properly without assistance the fleet angle should not be less than 1° . The fleet angle is that angle between the centre line of the first fixed sheave and the centre line of the rope leading to the drum (Feyrer, 2007).

3.17 Wire Rope Core

To investigate the effect of core types on the wire rope fatigue life, rope with fibre core and steel core are examined separately. According to bending test results on wire rope with fibre core, cores made from sisal and polypropylene (PP) give similar results, whereas core made from polyamide (PA) gives remarkably longer life. The result of this probably the polyamide material's strength is higher than the sisal and polypropylene. Increasing the mass of the core, provides longer fatigue life for the wire rope (Feyrer, 2007).

According to bending test results undertaken for steel cores, steel core coated with solid polymer (ESWRC), and steel core parallel to external strands (PWRC) provide longer bending life compared to the Independent wire rope core (IWRC) (Feyrer, 2007).



4. WIRE ROPE DISCARD CRITERIA

When the wire rope, uses inappropriate service area, it is possible to occur physical deterioration on its properties. For example, flexible wire rope that has outer wire diameter is less than 2 mm, deteriorate due to wear and corrosion.

Besides, when the wire rope used appropriately, it has finite but long life and in order to provide expected life it is required to be maintained during operation. Maintaining the wire rope, depends on the hoisting machine, the type of wire rope used and the environment. To improve the fatigue life of wire rope, it should be cleaned if it is possible, especially when it is passing through bending over sheaves the outer parts should be lubricated. In this chapter, the failure which could occur in service, and wire rope discard criteria will be described (Verreest & Ridge, 2005).

The safe use of rope is qualified by the following criteria:

- The nature and number of broken wires,
- Broken wires at the termination,
- The localized grouping of wire breaks,
- The rate of increase of wire breaks,
- The fracture of strands,
- Reduction of rope diameter, including that resulting from core deterioration,
- Decreased elasticity,
- External and internal wear,
- External and internal corrosion,
- Deformation,
- Damage due to heat or electric arcing,
- Rate of increase of permanent elongation.

All examinations shall take account of these individual factors, recognizing the particular criteria. However, deterioration will frequently result from a combination of factors giving a cumulative effect which shall be recognized by the competent person,

and which will reflect on the decision to discard the rope or to allow it to remain in service.

In all cases, the examiner should investigate whether the deterioration has been caused by a defect in the appliance; if so, he should recommend action to overcome the defect before fitting a new rope (TS ISO 4309, 1999).

4.1 Wear

Wear in wire rope split into two categories. These are abrasive wear and plastic wear. Abrasive wear are divided into two categories as external wear and internal wear. External wear on wire rope is formed due to friction between sheave and rope. External wear on wire rope can be seen as a flat surface on the contact points. It is increase when the rope has insufficient lubrication, excessive working speed, using sheave made by soft material, using inappropriate groove form. Wear decrease cross sectional area of wire rope and it decrease strength of wire rope (Verreet & Lindsay, 1996). Figure 4.1 shows an illustration of abrasive wear. Relative movement of wires or strands causes the internal abrasive wear. On the other hand plastic wear unlike abrasive wear, loss less materials on wire rope. Deformation on wire rope are formed due to manufacturing defect or very tight sheave's groove. These deformation may cause wire break due to increase pressures between strands.



Figure 4.1 : External abrasive wear on wire rope (Verreet & Lindsay, 1996).

External wear

Abrasion of the crown wires of outer strands in the rope results from rubbing contact, under pressure, with the grooves in the sheaves and the drums. The condition is particularly evident on moving ropes at points of sheave contact when the load is being accelerated or decelerated, and shows itself as flat surfaces on the outer wires.

Wear is promoted by lack of lubrication, or incorrect lubrication, and also by the presence of dust and grit. Wear reduces the strength of ropes by reducing the cross-sectional area of the steel. When owing to external wear the actual rope diameter has decreased by 7% or more of the nominal rope diameter, the ropes shall be discarded even if no wire breaks are visible.

4.2 Reduction of Rope Diameter Resulting from Core Deterioration

Reduction of rope diameter resulting from deterioration of the core can be caused by: internal wear and indentation, internal wear caused by friction between individual strands and wires in the rope, particularly when it is subject to bending, deterioration of a fiber core, fracture of a steel core, fracture of internal layers in a multi-strand composition.

If these factors cause the rope diameter (average of two diameter measurements normal to each other) to decrease by 3% of the nominal rope diameter for rotation-resistant ropes, or 10% for other ropes, the ropes shall be discarded even if no broken wires are visible.

Small deterioration may not be so apparent from normal examination, particularly if the rope stresses are well balanced throughout the individual strands. However, the condition may result in a high loss of rope strength, so that any suggestion of such internal deterioration shall be verified by internal examination procedures (TS ISO 4309, 1999). Where such deterioration is confirmed, the wire rope shall be discarded (Figure 4.2).

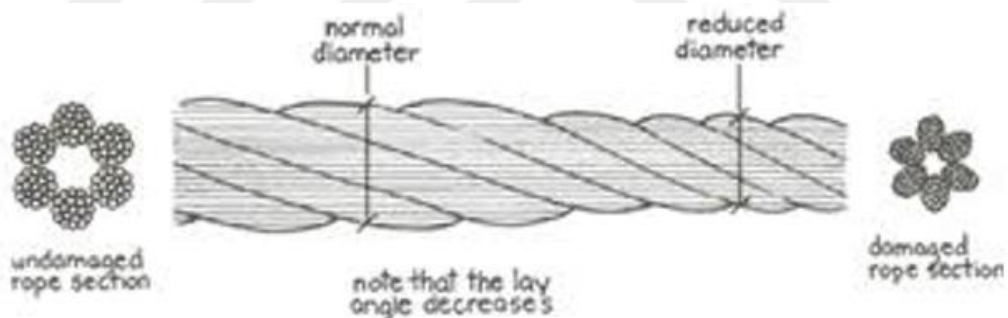


Figure 4.2 : Reduction of rope diameter (Verreet & Lindsay, 1996)

4.3 Corrosion

Corrosion may be external or internal, general or localized. According to (BS 6570, 1986), a wire rope should be discarded “when the surface of the wires is severely roughened or pitted, or if the wires are slack within the strands due to wastage”.

Corrosion occurs particularly in marine and industrial polluted atmospheres, and will not only diminish the breaking strength by reducing the metallic area of the rope but will also accelerate fatigue by causing the irregular surface from which stress cracking will commence. Severe corrosion may cause decreased elasticity of the rope. External corrosion, corrosion of the outer wires may be detected visually. Internal corrosion is

more difficult to detect than the external corrosion which frequently accompanies it, but the following indications may be recognized.

Variation in rope diameter: In positions where the rope bends around sheaves, a reduction in diameter usually occurs. However, in stationary ropes it is not uncommon for an increase in diameter to occur due to the build-up of rust under the outer layer of strands. Loss of gap between the strands in the outer layer of the rope, frequently combined with wire breaks in the strand gussets (Verreet & Lindsay, 1996). Confirmation of severe internal corrosion is justification for immediate rope discard (Figure 4.3).



Figure 4.3 : Corroded rope (Southwest Wire Rope Inc., 2008).

4.4 Decreased Elasticity

Under certain circumstances usually associated with the working environment, a rope may sustain a substantial decrease in elasticity and will be unsafe for further use. Decreased elasticity is difficult to detect: if the examiner is in any doubt, advice should be obtained from a specialist in ropes. However, it is usually associated with the reduction of rope diameter, elongation of the rope lay length, lack of gap between individual wires and between strands, caused by the compression of the component parts against each other, the appearance of fine, brown powder within the strand gussets, while no wire breaks may be visible, the wire rope will be noticeably stiffer to handle and will certainly have a reduction in diameter greater than related purely to wear of individual wires. This condition can lead to abrupt failure under dynamic loading and is sufficient justification for immediate discard (DIN 15020-2, 1974).

4.5 Fracture of Strands

If a complete strand fracture occurs, the rope shall be discarded (DIN 15020-2, 1974).

4.6 Deformation

Visible distortion of the rope from its normal formation is termed "deformation" and may create a change at the deformation position which will result in an uneven stress distribution in the rope.

Distinction is made between the following main deformations of rope on the basis of their appearance (TS ISO 4309, 1999).

- Waviness.
- Basket or lantern distortion.
- Strand extrusion.
- Wire extrusion.
- Local increase in the diameter of the rope.
- Local decrease in the diameter of the rope.
- Flattened portions.
- Kinks or tightened loops.
- Bends.

4.6.1 Waviness

This deformation, while it may not necessarily affect the strength of the rope, can transmit pulsation and procedure uneven ropes wear. When the rope is laid on a level of surface under no load, the maximum height of the wave should not be greater than the nominal rope diameter $+1/3$, otherwise the rope should be removed from service (Figure 4.4).



Figure 4.4 : Waviness (TS ISO 4309, 1999).

Waviness is a deformation where the longitudinal axis of the wire rope takes the shape of a helix. While not necessarily resulting in any loss of strength, such a deformation, if severe, may transmit a pulsation resulting in irregular rope drive.

After prolonged working, this will give rise to wear and wire breaks. In the case of waviness (Figure 4.5), the wire rope shall be discarded if:

$$d_1 > 4d / 3$$

where d is the nominal diameter of the rope and d_1 is the diameter corresponding to the envelope of the deformed rope, and the length of the rope under consideration does not exceed $25 d$.

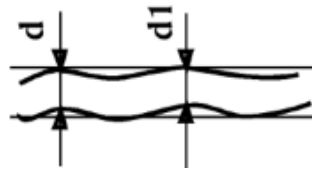


Figure 4.5 : Waviness (TS ISO 4309, 1999).

4.6.2 Birdcage (Basket deformation)

A birdcage (Figure 4.6) develops when the outer layer of strands became longer than the inner layer or layers. The condition may occur as a result of incorrect fitting, tight sheaves, shock loading, incorrect use of a swivel or the application of a heavy load to a new rope before the strands have settled into position. Ropes with a birdcage should be discarded.

This condition occurs in ropes having a steel center (or core) when the outer layer of strand has become dislocated, or when the outer layer becomes longer than the inner layer of strands. Such a condition may occur as a result of abrupt (snatch) loading of the rope from a slack condition. A basket or lantern formation is justification of immediate discard.



Figure 4.6 : Birdcage (Southwest Wire Rope Inc., 2008).

4.6.3 Strand Extrusion

This feature is frequently associated with basket or lantern deformation where the rope imbalance is indicated in the extrusion of the core. Strand extrusion (Figure 4.7) is justification for immediate discard.



Figure 4.7 : Strand extrusion (Southwest Wire Rope Inc., 2008).

4.6.4 Wire Extrusion

In this condition, certain wires or groups of wires rise up, on the opposite side of the rope to the sheave groove, in the form of loops. This feature usually results from shock loading. If the deformation is severe, there is justification for rope discard (Figure 4.8).



Figure 4.8 : Examples of wire extrusion (Southwest Wire Rope Inc., 2008).

4.6.5 Local increase in diameter of rope

A local increase (Figure 4.9) in rope diameter may occur and could affect a relatively long length of the rope. The condition usually relates to a distortion of the core (in particular environments, a fiber core can swell up owing to the effect of moisture) and consequently it creates imbalance in the outer strands, which become incorrectly oriented. A severe condition is justification for rope discard.



Figure 4.9 : Local increase in diameter of rope (Southwest Wire Rope Inc., 2008).

4.6.6 Local decrease in diameter of rope

A local decrease in the diameter of the rope is frequently associated with fracture of a core. Positions close to the terminations shall be carefully examined for such deformations. A severe condition is justification for rope discard.

Thinning (Figure 4.10) is a reduction in the diameter of the rope over a short length. It is often associated with older fiber cored ropes usually in areas of sustained heavy loads over sheaves. The disintegration and loss of the core can allow one of the

covering strands to take the place of the core. When this condition occurs in ropes with IWRC the distortion will most often be in the vicinity of the termination away from drum. The most likely cause is rope rotation which has allowed the rope to unlay, resulting in the overload and reduction in diameter of failure of the IWRC.



Figure 4.10 : Local decrease in diameter of rope (TS ISO 4309, 1999).

4.6.7 Flattened portions

Flattened portions occur as a result of mechanical damage; if severe, they are justification for rope discard. A flattening can be caused by bending the rope severely over the rim of a sheave or any sharp object with the wires on the inside of the bend being forced out of position (Figure 4.11).



Figure 4.11 : Flattened portions (Southwest Wire Rope Inc., 2008).

4.6.8 Kinks

Deformation caused by loop in a rope being tightened when the rope cannot rotate about its axis to release the torque. The tight bend or kink (Figure 4.12) thus formed can result in a serious loss of strength due to unbalance in the lay lengths. Ropes with kinks must be discarded.

A kink or tightened loop is a deformation created by a loop in the rope which has been tightened without allowing for rotation about its axis. Imbalance of lay length occurs, which will cause excessive wear, and in severe cases the rope will be so distorted that it will have only a small proportion of its strength remaining. A kink or tightened loop is justification for immediate discard.



Figure 4.12 : Kinks (TS ISO 4309, 1999).

4.6.9 Bends

Bends are angular deformations of the rope caused by external influence. The condition is justification for immediate discard (Figure 4.13).



Figure 4.13 : Bends (TS ISO 4309, 1999).

4.7 Loop Formations

Wires or groups of wires may form a line of loops parallel to the axis of the rope (Figure 4.14). This deformation is often caused by shock loading. Loop formations are a justification for discard.



Figure 4.14 : Loop formations (Southwest Wire Rope Inc., 2008).

4.8 Loose Wires

Where loose outer wires (Figure 4.15) are found without any adjacent mechanical damage, the most likely cause will be corrosion and the rope should be removed from service. Where loose wires have been caused by mechanical damage, a full examination will decide if the rope can remain in use.

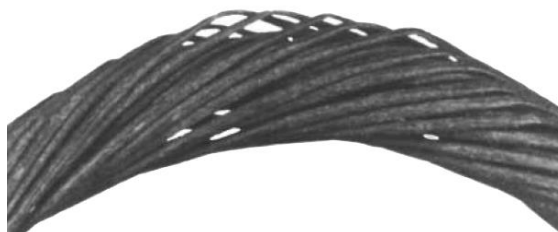


Figure 4.15 : Loose wires (Verreet & Lindsay, 1996).

4.9 Nodes

A node (Figure 4.16) is a local increase in rope diameter with the core easily visible between several covering strands. It can be caused by shock loading or, in the case of fibre main core ropes, by the absorption of moisture. A node is a justification for discard.



Figure 4.16 : Nodes (Verreet & Lindsay, 1996)

4.10 Misplaced Outer Wires

Misplaced outer wires are wires forced out of position along the line of the rope to form small flattened loops. This can be caused by bad drum spooling or by the rope being drawn across a sharp edge. Langs lay ropes are often worst affected. Misplaced outer wires are a justification for discard (Verreet & Lindsay, 1996).

4.11 Insufficient Lubrication

Ropes are usually lubricated with the help of impregnated oil. However the core may remain without oil because of heat affected. Lubrication condition can be understand to examining among strands. There must be full with grease or oil. Lubrication of wire rope should be made with oil has low viscosity. In this situation oil may penetrate to core. Insufficient lubrication can be seen in Figure 4.17.



Figure 4.17 : Insufficient lubrication (Verreet & Ridge, 2005).

4.12 Damage Due to Heat or Electric Arcing

Wire ropes are very good conductor of heat. Therefore, it can work in limited period of time, as long as heat absorbed by wire rope can transfer to the cooler region. However, when heat on the wires exceed 300° , wires lose $2/3$ of their tensile strength. Wire ropes which have been subjected to exceptional thermal effects, externally

recognized by the color produced, shall be discarded. Even if it is not observed that reduction on tensile strength, when the temperature reach or exceed the dropping point of the lubricant it may expected to reduce on fatigue endurance. It can be seen in Figure 4.18 wire rope which is exposed to high temperature.



Figure 4.18 : Wire rope exposed to high temperature (Verreet & Ridge, 2005).

4.13 Damage Caused by Heat

Heating rope wires to approximately 300 °C and over will lead to considerable reduction in tensile strength of the wires (Figure 4.19). Wire ropes which have been subjected to excessive heat must be discarded.

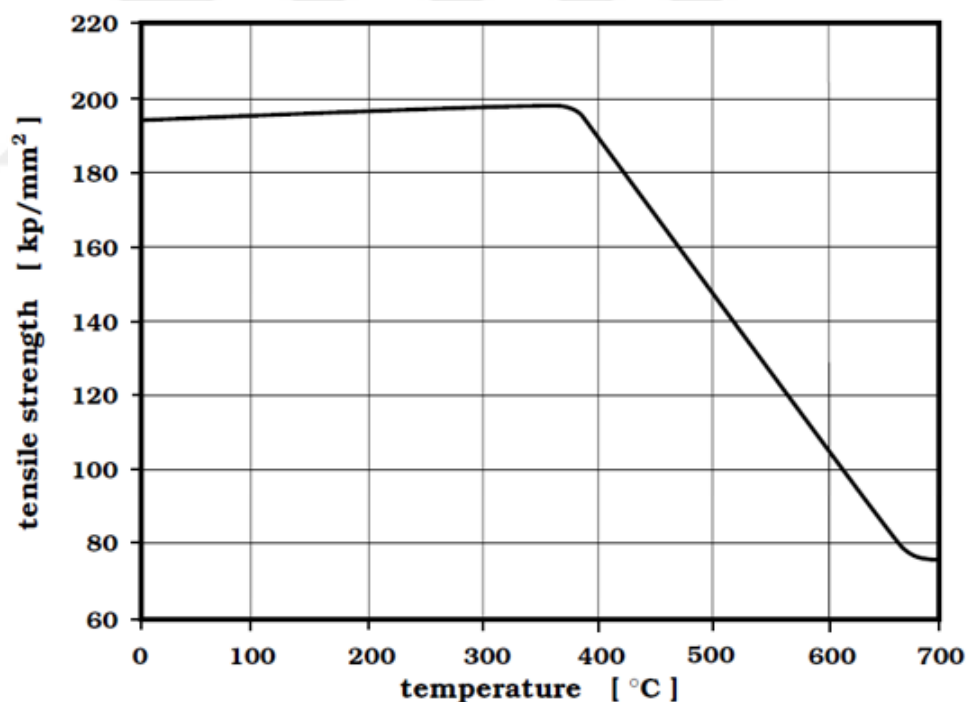


Figure 4.19 : Relation between temperature and tensile strength.

4.14 Broken Wires

A wire rope must be discarded if the permissible number of wire breaks is reached or exceeded. It must also be replaced when local concentrations wire breaks occur.

4.14.1 Nature and number of broken wires

The overall design of a crane is such that it does not permit indefinite rope life. In the case of 6 and 8 strand ropes, broken wires occur principally at the external surface. This does not apply to wire ropes having a number of layers of strands (typically multi-strand compositions), where the majority of breaks occur internally and are therefore "non-visible" fractures. When establishing rejection criteria for rotation-resistant ropes, consideration shall be given to the rope composition, length of service and the way in which the rope is being used. Guidance to the number of visible broken wires which shall give rise to rejection is given in Table 4.1 and Table 4.2. Particular attention shall be paid to any localized area, which exhibits a dryness or denaturing of the lubrication.

4.14.2 Broken wires at the termination

Broken wires at, or adjacent to, the termination, even if few in number, are indicative of high stresses at this position and may be caused by incorrect fitting of the termination. Investigation of the cause of this deterioration shall be made, and where possible, the termination should be remade, shortening the rope if sufficient remains for further use.

Table 4.1 : Guidance for the number of broken wires in round strand ropes working in steel sheaves (Verreet & Lindsay, 1996).

Number of load-bearing wires in outer strands	Typical examples of rope compositions	Number of visible broken wires related to the fatigue of the rope in a crane which gives rise to rejection							
		Classification groups for M1, M2, M3 and M4 mechanisms				Classification groups for M5, M6, M7 and M8 mechanisms			
		Ordinary over a length of		Langs		Ordinary over a length of		Langs	
		6d	30d	6d	30d	6d	30d	6d	30d
$51 \leq n \leq 75$	8x26+8x17+4x7	3	6	2	3	6	12	3	6

Filler wires are not regarded as load-bearing wires and are therefore excluded from the examination. In ropes having a number of layers of strands, only the visible outer layer is considered. In ropes having a steel core, this is regarded as an internal strand and is not considered.

In the case of a calculation for numbers of visible broken wires, the value is rounded to a whole number.

d = nominal diameter of the rope.

Table 4.2 : Number of visible broken wires related to fatigue of the rope in a crane, which gives rise to rejection (Verreet & Lindsay, 1996).

Classification groups for M1, M2, M3 and M4 mechanism		Classification groups for M5, M6, M7 and M8 mechanism	
Over a length of		Over a length of	
6d	30d	6d	30d
2	4	4	8

When a wire rope works totally or partly on synthetics or metallic with synthetic warranties, the wires breaking can happen in the inside, without any visible breaking or any important damages outside.

4.14.3 Localized grouping of broken wires

Where broken wires are very close together, constituting local grouping of such breaks, the rope shall be discarded. If the grouping of such breaks occurs in a length less than $6d$ or is concentrated in any one strand, it will be prudent to discard the rope even if the number of wire breaks is smaller than the maximum number indicated in Tables 4.1 and 4.2.

4.14.4 Rate of increase of broken wires

In applications where the predominant cause of rope deterioration is fatigue, the commencement of broken wires will begin after a certain period of usage, but the number of breaks will progressively increase at ever-shortening intervals. In these cases, it is recommended that careful examination and recording of the increase of broken wires should be undertaken with a view to establishing the rate of increase of the breaks. An application of this "law" may be used in deciding the future date for rope discard.

4.15 Martensitic Embrittlement

Martensite is very hard and rigid form of steel crystalline structure. It occurs as a result of rapid cooling after it heats over the critical temperature and it causes embrittlement. Martensitic embrittlement can be occurred on the contact area while wire ropes multiple

wounded on sheave. In this case, the wire rope is heated due to the contact between wounded part of rope. Martensitic structure causes the crack and propagate inward (Yetiştiren et al., 2007). Figure 4.20 shows a crack in the wire which occur because of martensitic embrittlement.

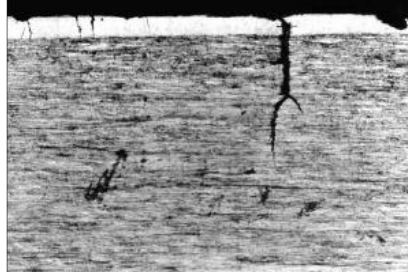


Figure 4.20 : Martensitic embrittlement (Yetiştiren et al, 2007).

4.16 Damage Occured due to External Factors

Wire ropes sometimes can damaged on the service. Wire rope can crush steel object, or steel object can be crush wire rope, or wire rope can be dragged on a hard surface. Figure 4.21 shows the failure on wire ropes which occurred due to the impact of prong object (Verreet & Ridge, 2005). In this case rope must be discared.

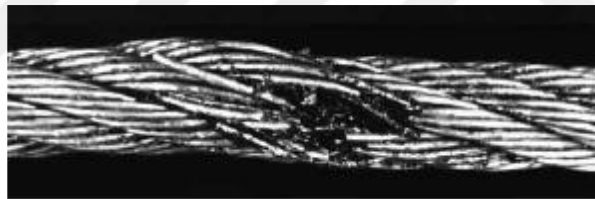


Figure 4.21 : Damage occurred due to external factors (Verreet & Ridge, 2005).

5. EXPERIMENTAL STUDY

5.1 Introduction

Wire ropes, which are mostly used mining application, winches, cable cars, and elevators, under constant tensile force it is running up on sheave. When the ropes in loading process, it is becoming straight from curve, and unloading it is becoming curve from straight form. For this reason, the wire ropes are subjected to fatigue due to repeated bending movement. In the literature, that kind of fatigue called as bending over sheave BoS fatigue. This type of fatigue is particular for the rope applications, which are used with sheave. Even if the load is constant, the rope has finite life since presence of repeated bending by movement of the rope over sheave. In this thesis, bending over sheave BoS fatigue called as a bending fatigue. Steel wire rope subjected to bending fatigue N (cycles) are determined based on the type of rope composition, diameter of sheave (D), tensile load, and corrosion level. Therefore, two different wire rope compositions have selected. These wire rope samples have prepared for bending fatigue experiment. The bending fatigue tests have been carried out with specific test equipment. Fatigue life for each sample have been determined. The results, which are obtained from two different type of compositions have been compared. As a result of these experiments, the most important parameters such as tensile load, diameter ratio and corrosion effects on wire rope were determined.

5.2 Wire Rope Samples Used in the Experiments

In this thesis, two different wire rope compositions have investigated experimentally. These are 6 x 36 Warrington Seale and 32 (W) x 7 soliflex rotation resistant wire ropes. Figure 5.1 shows that 6 x 36 Warrington Seale ropes and its cross section view. Figure 5.2 shows rotation resistant wire rope and its cross section view. In order to obtain comparable results, technical parameters such as diameter of wire ropes, wire grades, has been selected same.



Figure 5.1 : 6 x 36 Warrington Seale wire rope sample and its cross section view.



Figure 5.2 : 32(W) x 7 soliflex strands rotation resistant wire rope sample.

Figure 5.1 shows cross section view of 6 x 36 Warrington Seale wire rope sample, which has examined in this thesis. This rope has 6 strands, and each strand has 36 wires which has different diameter. Inner wires are Warrington, outer wires are Seale sequences, and has independent wire rope core (IWRC). Wire rope core is rope itself and it is called as Independent Wire Rope Core (IWRC)". These types of wire ropes are not resistant against the rotation therefore tends to open. This should be considered on end connection. Table 5.1 shows the technical properties of 6 x 36 Warrington Seale rope. It has 10 mm in diameter, 1960 MPa wire grade, preform, 6 strand, right hand regular lay (sZ). It has 71,6 kN minimum breaking load, and steel core. 6 x 36 Warrington-Seale wire rope which is used in this thesis has 14 outer wires in each strand. When the rope works with sheave, outer wires are contact to sheave surface.

Table 5.1 : 6x36 Technical properties of 6 x 36 Warrington-Seale wire rope.

Number of strands	6
Compositions	6 x (1-7-7+7-14) + IWRC
Diameter	10 mm
Wire grade	1960 MPa
Lay type	Right hand regular lay (sZ)
Minimum breaking load	71,6 kN

Early studies showed that, a rope which has relatively few outside wires is highly resistant to abrasive wear but it has markedly less resistant to bending fatigue because of the resulting increased stiffness associated with fewer outside wires. The studies performed that when number of outer (external) wire for each strand increases, fatigue resistant increases, when number of outer wires reduce, wear resistance increase.

That means while using wire rope which has more thicker wires and less number of outer wires (6 x 7, 6 x 19S etc.) while improving wear resistant of wire ropes, whereas wire rope which has more thinner wires and more number of wires has been used (6 x 64, 6 x 49 etc.) increases the resistance of fatigue. 6 x 36 Warrington-Seale ropes have great fatigue resistant, but also it has relatively good wear resistant. Because of these features, 6 x 36 Warrington Seale rope are frequently used for lifting heavy loads in mining industry, oil industry, and with different sorts of crane.

32 (W) x 7 soliflex rotation resistant wire rope's cross section view can be seen in Figure 5.2. This rope has five strand layers on one steel core. These strands wrapped opposite direction, these features allowed safety against to rotation when the rope installed. Technical properties of this wire rope can be seen in Table 5.2. It has 32 strands, 224 wires, and 10 mm in diameter, preform, 1960 MPa wire grade, left hand regular lay (zS) minimum breaking load 76,5 kN.

Table 5.2 : Technical properties of Soliflex 32 (W) x 7 rope.

Number of strands	32
Number of wire	32 (W) x 7
Diameter	10 mm
Wire grade	1960 MPa
Rope lay	Left hand regular lay (zS)
Minimum breaking load	76,5 kN

Specific properties of soliflex rotation behaviour, robustness against pinching and abrasion, good reeling properties on rope pulleys. Rotation resistant rope which has examined in this thesis has very flexible and high breaking load according to other type of wire rope composition which has same diameter. It has good reeling properties on sheave, and pretty good robustness against pinching and abrasion. That type of rope can be use with free end connection against the rotation.

5.3 Preperation of Wire Rope Sample

In this study to attain comparable results two different diameter of sheaves have been used. The first of these has 250 mm diameter (D=250 mm) steel sheave, and second has 170 mm (D=170 mm) steel sheve. Wire rope samples length has been chosen according to sheave diameter. When 250 mm diameter sheave used, length of rope sample should be 4770 mm. The reason of this, constant tensile load which should be applied during test created in a right way. To cut wire rope sample in specified length

it should be marked to the desired length, then the rope sample attached one side of rope tensioning device (Figure 5.3) and aid of arm it should be stretched the other end.



Figure 5.3 : Rope tensioning device.

In order to cut wire rope sample in specified length, both side of marked region should be safety handle applied. Wire rope with strand safety handle length should be minimum two times diameter of wire ropes. For preform wire ropes, both side of marked region one safety handle is usually sufficient. For non-preform rotation resistant wire rope, and parallel closed wire rope both side of cutting region at least two safety handle is recommended. Wire rope samples used in this thesis are preformed both side of cutting region 5 mm distance from cutting region 10 mm length and 70 mm distance, length of safety handle 45 mm is wrapped with 1 mm diameter connection wire. Figure 5.4 shows the safety handle for one side of ropes and cutting procedure made by steel cutting machine. Figure 5.5 shows the steel cutting machine.



Figure 5.4 : Safety handle.



Figure 5.5 : Steel cutting machine.

In order to fix wire rope samples, which have already cut appreciable length, end connection must be made for each end. Firstly, safety handle which is shown in Figure 5.4 10 mm long region is removed and the rope strands are separated individually, up to a distance 70 mm then separated strands are separated to wires in same way. One side of the wire rope at the end of the separation process can be seen in Figure 5.6. The same operation have been done for both type of rope.



Figure 5.6 : Separated region of wire rope.

After separation operation the rope sample's separated region have been cleaned from grease by the help of gasoline. Figure 5.7 shows cleaning operation for rotation resistant rope sample.

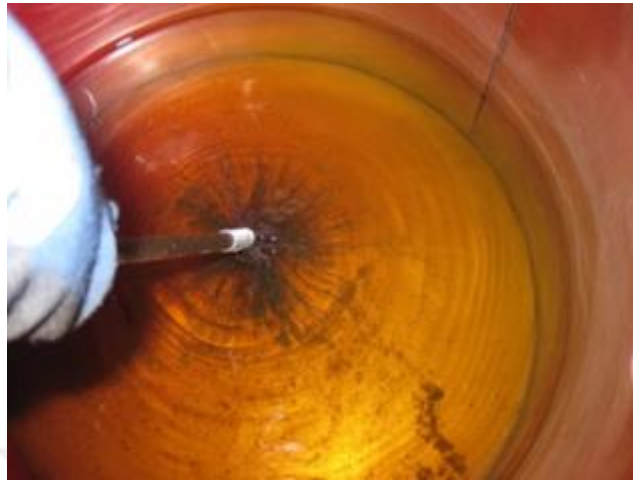


Figure 5.7 : Cleaning operation with gasoline.

For chemical cleaneasing of the wire rope end is kept into the acid bath for a period of time (Figure 5.8). This solution used for cleaning the rope end from oil, rust, and sediment etc. As shown in Figure 5.9 cleaning in acid bath, is removed impurity dirt and grease and at the end of the rope, the rope end has more brighter surface than before.

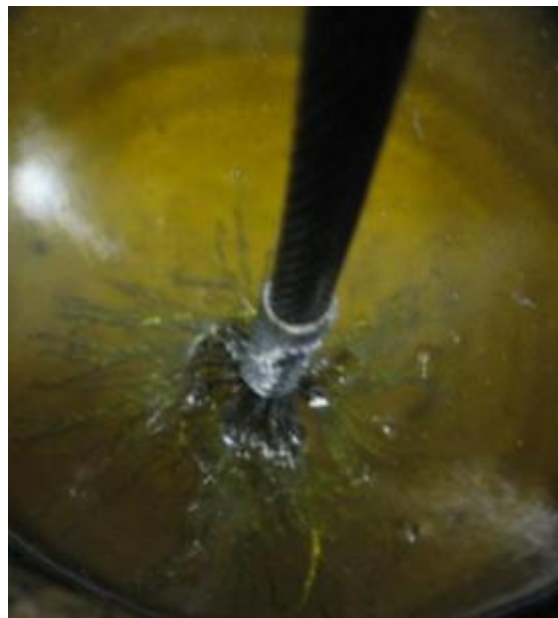


Figure 5.8 : Acid bath.



Figure 5.9 : Cleaned side of wire rope.

After completion of surface cleaning operations, rope end is passed through casting mold. In order to make molding operation, cast alloy and furnace which can be reached up to casting temperature are required. Figure 5.10 demonstrate that melting stove which was used for this study. This melting stove was heated until the temperature reach 345°C. Lead alloy TEGO-V3 was used, to make end connection. This alloy is specific for wire rope end connection. Table 5.3 shows the chemical and physical properties of TEGO-VG3 alloy.



Figure 5.10 : Melting stove.

Table 5.3 : Chemical and physical properties of TEGO-VG3 alloy.

Chemical composition (% mass)	
Sn	10
Sb	10
Cu	0.5
As	0.5
Cd	2
Pb	77
Tensile test (MPa)	
0.2 % Yield strength	38
Tensile strength	74
Young`s module	30000
Physical properties	
Density	9,9 kg/dm ³
Melting point	242 °C
Temperature	340 °C - 360 °C

Chemically cleansed end of the wire rope has been kept for a while in cast alloy furnace which is reached 345 °C. After that rope end is immersed in zinc clorid solution that called TEGO-ROPTIN less than a minute. This solution, in addition to zinc clorid, contains small amount of ammonium salt and free acid, and it is caustic. The reason of this process, removal of oxide, and provide better adhesion between casting alloy and wires. Then the end of the rope positioned in the cast mold (Figure 5.11). Molten cast alloy pour from the top of the mold with a scoop. At the end of the casting process, wire rope end becomes as in Figure 5.12. These processes should repeat for both ends.



Figure 5.11 : Casting processes.



Figure 5.12 : Wire rope end when cast process finish.

5.4 Corrosion Procedure

The wire rope used in this study 6 x 36 Warrington-Seale, and 32 (W) x 7 solifilex rotation resistant which are mostly exposed in corrosion effect in service. These ropes have the same properties as the wire ropes used in the hoisting application. This allowed the corrosion affected bending fatigue results to be directly applicable to wire ropes in service. For the corrosion tests, the accelerated salt spray fog environment has been used. The salt spray tests were carried out according to (ASTM B117, 2011) specification. The corrosive solution was prepared by dissolving 5 parts by mass of sodium chloride in 95 parts of water. In this study only one meter from the middle of wire ropes which is enforced bending over sheave exposed to corrosion affect. For comparison, all experiments were carried out also for the non-corroded material.

The procedure used in practice was to make a container of solution and expose all the test samples for a single exposure level together in the same mixture. The corrosion test setup has been created with a metal box above the oven and sand used for distribute the heat all over the box homogeneously (Figure 5.13). Corrosion of samples was accomplished by the utilization of a corrosion cell. It can be seen in Figure 5.14. The solution compositions for the corrosion bath 5% wt. of NaCl and 95% wt. of H₂O to simulate the aggressive environment.



Figure 5.13 : Building stage of corrosion cell.



Figure 5.14 : Corrosion cell.

In corroding the specimens, the desired result was to expose all samples to the same corrosive environment for varying lengths of time, in this case, for one, two, and three weeks for Warrington Seale rope samples and one to twelve weeks for Soliflex rotation resistant wire rope sample. Figure 5.15 and Figure 5.16 show the corrosion level of Warrington Seale rope and rotation resistant wire rope respectively.

	6x36 Warrington Seale rope sample without corrosion.
	6x36 Warrington Seale rope sample kept in salty water solution for one week.
	6x36 Warrington Seale rope sample kept in salty water solution for two weeks.
	6x36 Warrington Seale rope sample kept in salty water solution for three weeks.

Figure 5.15 : Pre-corroded 6x36 Warrington Seale wire rope with three levels.

	32 (W) x 7 soliflex rotation resistant rope sample without corrosion.
	32 (W) x 7 soliflex rotation resistant rope sample kept in salty water solution for one week.
	32 (W) x 7 soliflex rotation resistant rope sample kept in salt water solution for two weeks.
	32 (W) x 7 soliflex rotation resistant rope sample kept in salty water solution for three weeks.
	32 (W) x 7 soliflex rotation resistant rope sample kept in salty water solution for four weeks.
	32 (W) x 7 soliflex rotation resistant rope sample kept in salty water solution for five weeks.
	32 (W) x 7 soliflex rotation resistant rope sample kept in salty water solution for six weeks.
	32 (W) x 7 soliflex rotation resistant rope sample kept in salty water solution for seven weeks.
	32 (W) x 7 soliflex rotation resistant rope sample kept in salty water solution for eight weeks.
	32 (W) x 7 soliflex rotation resistant rope sample kept in salty water solution for nine weeks.
	32 (W) x 7 soliflex rotation resistant rope sample kept in salty water solution for ten weeks.
	32 (W) x 7 soliflex rotation resistant rope sample kept in salty water solution for eleven weeks.

Figure 5.16 : Pre-corroded soliflex wire rope with ten levels.

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. 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 investigation a number of fatigue 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. Because wire rope always used with lubrication. Wire Rope Bending Test

5.4.1 Test principle

While wire ropes run over sheaves, the wires which composed the whole rope are loaded by constant and variable stresses and pressure. Even if all of these stresses and wire endurance under these stresses are known, it is impossible to determine the endurance of a particular wire rope. This is the case partly because the relative motion causes the wires to become worn and also because of irregularities which result in neighbouring wires being loaded by very different tensile stresses. Therefore, wire ropes running over sheaves always have a finite life and the number of bending cycles can be only evaluated by wire rope bending fatigue tests (Feyrer, 2007). To achieve bending fatigue test of steel wire ropes, the basis of simple bending mostly used in application can be seen in Figure 5.17.

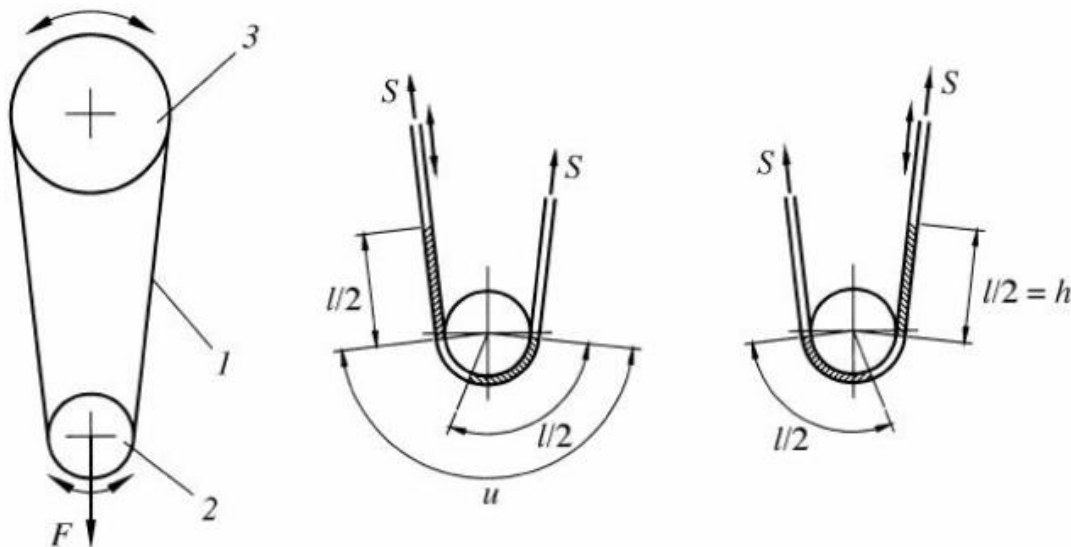


Figure 5.17 : Simple bending (Gorbatov et al., 2007).

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 Figure 5.17 1,2,3 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 Figure 5.17, h is the rope stroke, l is bending length, u is contact length between rope and sheave. Wire ropes in application can be bend over sheave as simple bending or reverse bending. Bending fatigue test, which is shown in Figure 5.17 is simple bending.

Combined fluctuating tension and bending means that the tensile force will be enlarged before the rope is bent and reduced again afterwards. In this case, the longitudinally fluctuating wire stresses are composed of those of the rope bending and those of the changing tensile force. These combined fluctuating stresses are much higher than in the case of simple bending under a constant tensile force. Therefore, this combined fluctuating bending and tensile force reduces the rope endurance enormously.

In the literature the bending cycles over the sheave (N) can be represented two different indices. These are N_{rev} , N_{sim} . In order to determine number of cycle $N=N_{sim}$ of simple bending cycle on simple bending h the rope stroke is important. When the stroke h is smaller than u the rope contact bow with the test sheave, in each cycle of test machine, the wire rope is bent by one simple rope bending. The number of machine cycles Z is equal to the number of the rope's simple bending cycles $N = N_{sim}$. The bending length l on two bending zones h is

$$l = 2h, \text{ and } N = N_{sim} = Z, \text{ for } h < u. \quad (5.1)$$

If the rope stroke h is greater than the rope contact bow u with the test sheave, then for each machine cycle the rope is bent twice. For the number of machine cycles Z , the number of simple rope bending cycles is $N = N_{sim} = 2Z$. In this case the rope bending length is

$$l = h - u, \text{ and } N = N_{sim} = 2Z, \text{ for } h > u. \quad (5.2)$$

On both sides of this bending length $l = h-u$ with the number of bending cycles $N = N_{sim} = 2Z$ there are two bending zones of the length u with the number of bending

cycles $N = N_{\text{sim}} = 1Z$. Of course these bending zones have no influence on the endurance of the rope.

Reverse bending cycles without additional simple bending cycles on the same bending length are only possible on a relatively small rope bending length (Figure 5.18). If the rope stroke is just $h = u + a$, then on a bending length $l = u$ for the machine cycle Z there are two reverse bending cycles $N_{\text{rev}} = 2Z$. On other zones, the rope is only bent by simple bending cycles.

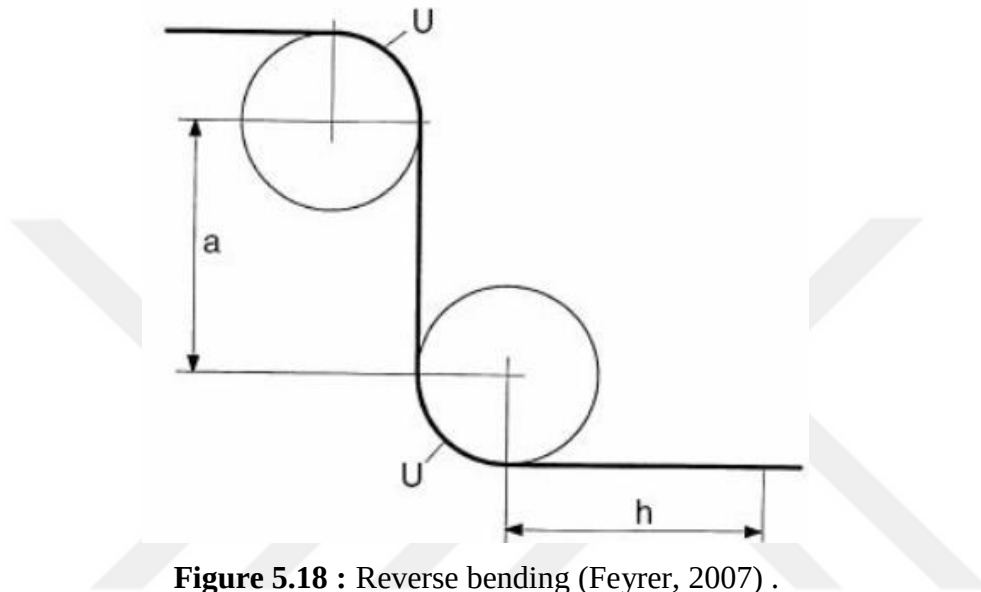


Figure 5.18 : Reverse bending (Feyrer, 2007) .

In this case, during the bending movement, external wire exposed to tension on upper sheave, and it exposed to compressive stress on lower sheave. Wire rope operating in this way has less service life as regards to simple bending. In this thesis, test machine which has provided simple bending was used.

5.4.2 Test machine used in the experiments

Experimental part of this study was carried out in University of Stuttgart Institut für Fördertechnik und Logistik, Rope Technology Laboratory. Bending fatigue test machine the principle of test has been explained in chapter 5.5.1, and the machine and its basic elements shown in Figure 5.19.

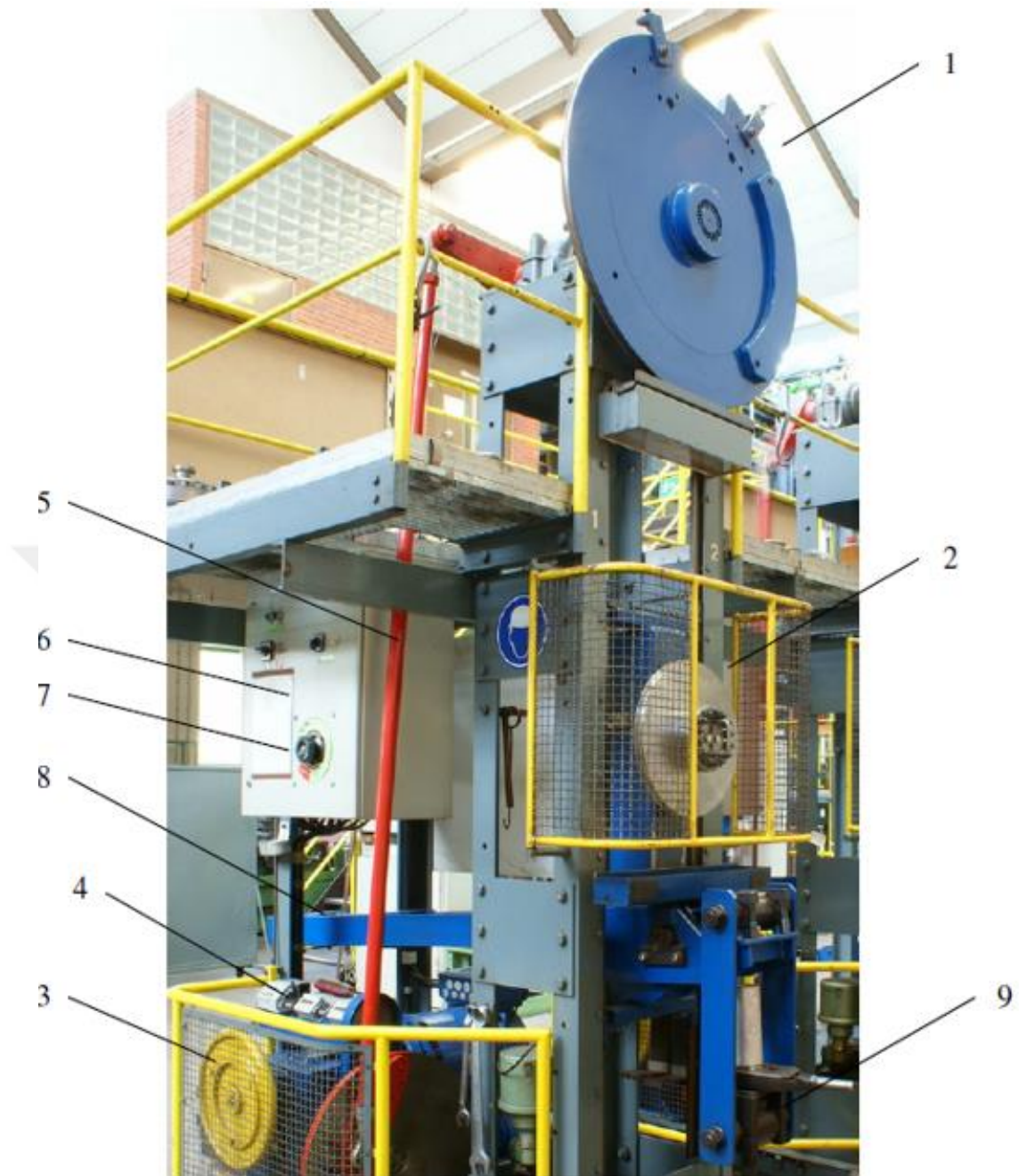


Figure 5.19 : Bending fatigue test machine.

Bending fatigue test machine which is shown in Figure 5.19 and its elements are as follows:

- 1: drive sheave
- 2: test sheave
- 3: electric motor
- 4: counter
- 5: crank which transmits the rotational movement of motor to drive pulley
- 6: electric connection box

7: speed control button

8: lever mechanism which provides constant tension load to test rope

9: compression screw which transmits the load to the test rope

Test set up driven by Blocher motor, which has 9.4 kW power, maximum rotation speed is 1560 rev/h (3). Rotation movement, with the aid of gear and clutch, transmitted the red disc shown in Figure 5.19 and crank (5) is connected with disc. Rotation speed of test machine can be changed by speed control button (7). Test machine which used in this study has maximum 2750 rev/h rotation speed. The parameter which indicated the revolution speed's maximum are temperature between sheave and wire rope, vibration, and machine design limitation. Test machine's cycles are counted by counter (4) until the rope broken. Continuity of wire rope movement during test, is provided by drive sheave (1) which is connected to crank. Drive sheave (1) moving back and forth along a certain stroke and this continuous movement causes wire rope breakage on test sheave (2). Drive sheave (1) is used in this study has 1 meter in diameter and all tests are performed with same drive sheave. For the smaller test sheave diameter and groove geometry can be considered as test parameter. Drive sheave and test sheave, had been assembled in suspended position, so different diameter ropes or sheave can be easily attached and detached. Also, with this position, provided comfortable way of making measurements of stopping the machine and wire rope fracture during testing has been observed. In this study, two different test sheaves have been used. Figure 5.20 and 5.21 show the test sheaves 250 mm in diameter and 170 mm in diameter respectively.

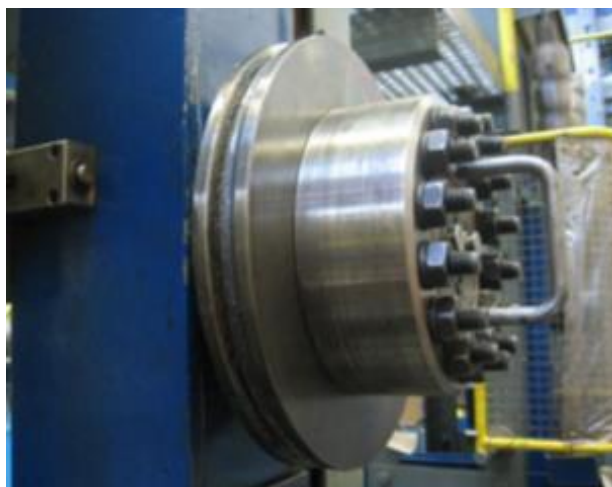


Figure 5.20 : Test sheave 250 mm in diameter.



Figure 5.21 : Test sheave 170 mm in diameter.

All shaves are used in this study wire rope contact surfaces are round shape as shown in Figure 5.22 and manufactured by hardened steel.

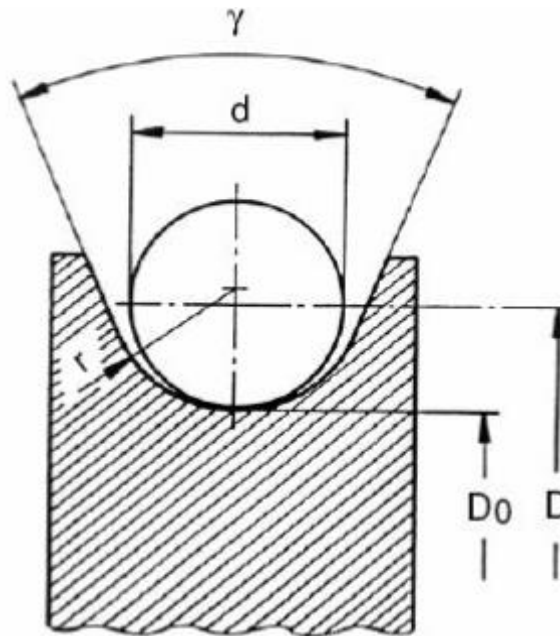


Figure 5.22 : Sheave groove geometry (Feyrer, 2007).

Here, d ; diameter of wire rope, r ; groove radius, γ ; groove angle, D ; distance between wire rope center and diameter of sheave, D_0 ; groove base diameter. Sheaves are used in this study equation in (5.3) was used (Feyrer, 2007).

$$r = 0,53.d \text{ ve } \gamma=60^\circ \quad (5.3)$$

An important element of the wire rope bending fatigue machine is lever mechanism that provides constant tensile load. As in Figure 5.23 to aid of weight placed at one end of the balance arm, constant tensile load is applied through the test shave at the other end to the test rope. Rotation speed can be controlled by speed control button (Figure 5.24).



Figure 5.23 : Weights on balanced arm.



Figure 5.24 : Speed control button.

These weights are lifted by compression screw (9) which is shown in Figure 5.25. While weight remove from floor, test shaves center axis moves downwordly, so that test rope strached and constant tensile load is created. In order to determine constant tensile load amount, the tensile load and the sheaves and auxiliary elements used in test are considered and calculated by specific formulas. These formulas shall not given here.



Figure 5.25 : Compression screw.

The wire ropes are cut specified length and which explained in detailed in chapter 5.3 have to be connected to the test machine. Therefore, the wire rope samples preparation processes are repeated and new support wire ropes, which 3 meter in length are prepared. The main purpose of these support rope, which is work on drive sheave, with the motion recieved from drive sheave, provide back and forth movement to the test rope in h stroke length. In order to provide this movement, support rope pass through the drive sheave, and it connects with test ropes both ends. This is the only purpose of using support rope. It does not effect the result. Figure 5.26 shows the connection between support rope and test rope. Test machine is ready to run in this figure.



Figure 5.26 : Wire rope end connections.

Figure 5.27 shows the counter test machine's cycles are counted until the rope broken.



Figure 5.27 : Counter.

5.5 Experimental Result

5.5.1 Introduction

The measurements and observations during test made by the investigator to be explained, then the experimental results will be shared. During the test, test machine stopped regularly, and test rope was observed by investigator to identify whether to reach discard criteria which is explained chapter 4. Whenever machine stopped, test

ropes bending region in $6d$ and $30d$ length, broken wire detected, and wire rope diameter measured again.

5.5.2 Effect of composition on pre-corroded wire ropes

In order to investigate the combine effect of wire rope composition and corrosion two different type of wire ropes (6 x 36 Warrington Seale and 32(W) x 7 Soliflex rotation resistant rope) have been used. To obtained comparable results both type of ropes have been kept in same corrosion cell for certain period of time. Bending over sheave test have been performed according to DIN 15020-2 standard. Bending tests have been performed with 17,0 kN tensile load and the shave 250 mm in diameter. Both rope are 10 mm in diameter. Test results according to stated parameters can be seen in Table 5.4.

Table 5.4 : Test results on pre-corroded wire rope with different rope composition ($D/d=25$, $S/d^2=170\text{N/mm}^2$).

Test Number	Rope composition	Corosion Level	Fatigue Life Endurance (N)	Reduction in Fatigue Life %
Test 1	6 x 36 WS	Reference test	127900	-
Test 2	6 x 36 WS	1 week	91278	28,64%
Test 3	6 x 36 WS	2 weeks	75171	41,23%
Test 4	6 x 36 WS	3 weeks	62076	51,46%
Test 5	32 (W)x7	Reference test	33140	-
Test 6	32 (W)x7	1 week	31920	-
Test 7	32 (W)x7	2 weeks	33368	-
Test 8	32 (W)x7	3 weeks	34628	-
Test 9	32 (W)x7	4 weeks	32258	-
Test 10	32 (W)x7	5 weeks	33464	-
Test 11	32 (W)x7	6 weeks	32156	-
Test 12	32 (W)x7	7 weeks	30465	-
Test 13	32 (W)x7	8 weeks	23852	28,02%
Test 14	32 (W)x7	9 weeks	17852	46,13%
Test 15	32 (W)x7	10 weeks	12476	62,35%
Test 16	32 (W)x7	11 weeks	9328	71,85%
Test 17	32 (W)x7	12 weeks	4498	86,40%

As it can be seen from Table 5.4, BoS fatigue lifetime of 6 x 36 Warrington-Seale rope and 32 (W) x 7 soliflex rotation resistant rope reduce as corrosion time increases. However, 6 x 36 WS rope is more sensitive to corrosion.

According to reference test, for 6 x 36 Warrington-Seale rope, when specific tensile load $S/d^2 = 170 \text{ N/mm}^2$ and diameter ratio $D/d=25$, the rope sample was broken 127900 cycles. When the same parameter applied for pre-corroded specimens the lifetime of wire rope reduce dramatically. If the 6 x 36 Warrington-Seale rope samples have kept in salt water solution for one week, two weeks and three weeks BoS fatigue lifetime reduce 28,64%, 41,23%, and 51,46% respectively. Figure 5.28 shows the experimental results of 6 x 36 WS rope BoS fatigue life with different corrosion level.

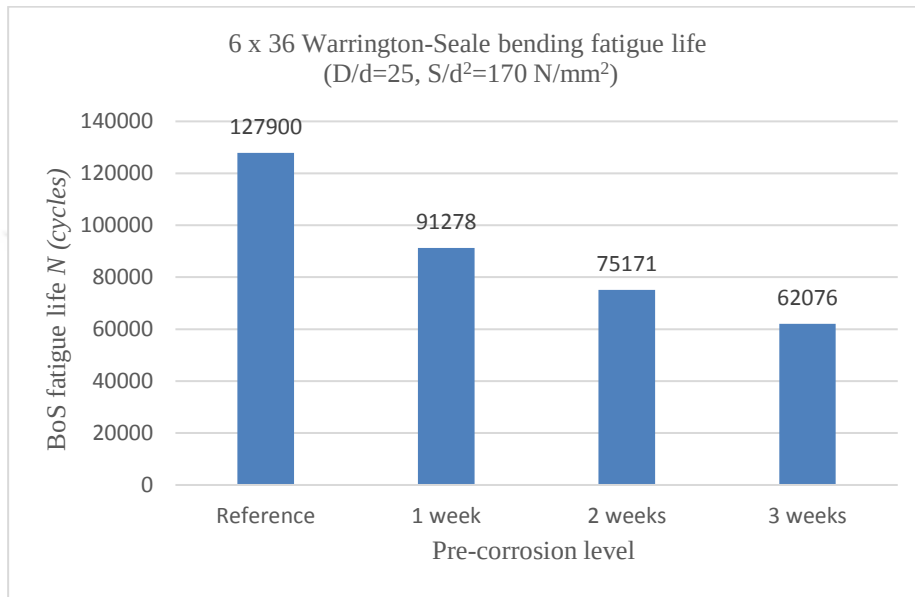


Figure 5.28 : 6 x 36 Warrington Seale rope BoS fatigue life with different corrosion level.

On the other hand, for 32 (W) x 7 soliflex rotation resistant rope the penetration time is longer and according to test results $S/d^2 = 170 \text{ N/mm}^2$ and diameter ratio $D/d=25$, the rope sample was broken after 34140 cycles. However, influence of corrosion until 8 weeks were not considerable. Results shown in Figure 5.29 were in variation up to eight weeks. After eight weeks remarkable influence has begun to observe. If the 32 (W) x 7 soliflex rotation resistant rope sample keep in salt water solution for eight, nine, ten, eleven, and twelve weeks, BoS fatigue lifetime reduce 28.02%, 46,13%, 62,35%, 71,85%, and 86.4% respectively.

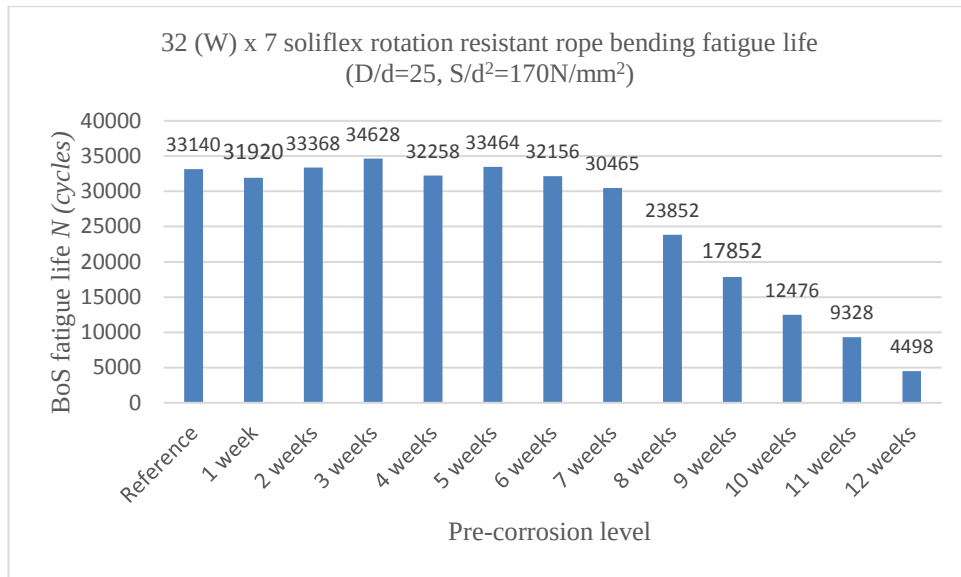


Figure 5.29 : 32 (W) x 7 rotation resistant rope BoS fatigue life with different corrosion level.

5.5.3 Effect of tensile load on pre-corroded wire rope

To investigate the combine effect of the tensile load and corrosion 6 x 36 Warrington Seale wire rope has tested with two different tensile load 17.0 kN and 11.7 kN. The suitable tensile load has been selected from Feyrer's book (Feyrer, 2007). To obtained comparable results, all samples have been kept in same corrosion cell for certain period of time. Bending tests have been performed with the sheave 250 mm in diameter. Test results according to stated parameters can be seen in Table 5.5.

Table 5.5 : Effect of tensile load on pre-corroded 6 x 36 Warrington Seale rope.

Test number	Specific Tensile Load S/d ² (N/mm ²)	Diameter ratio (D/d)	Corrosion Level	Fatigue Life Endurance (N)	Reduction in Fatigue Life %
Test 1	170	25	Reference test	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 18	117	25	Reference test	181257	
Test 19	117	25	1 weeks	170159	6,12 %
Test 20	117	25	2 weeks	146288	19,3 %
Test 21	117	25	3 weeks	116721	35,6 %

When the specific tensile load decreases from 170 N/mm² to 117 N/mm² fatigue lifetime of the 6 x 36 WS rope increase 41%. Many studies in the literature have presented the relation between lifetime of the wire rope and tensile load (Feyrer, 2007; Onur & Imrak, 2012). However, in order to understand the combine effects of corrosion and tensile load Figure 5.30 should be examined in detail. In this chart horizontal axis indicates the corrosion level and vertical axis indicates the bending life cycles. Red columns refer to the life cycles of the rope under 11.7 kN tensile load while blue columns refer to life cycles for 17.0 kN tensile load.

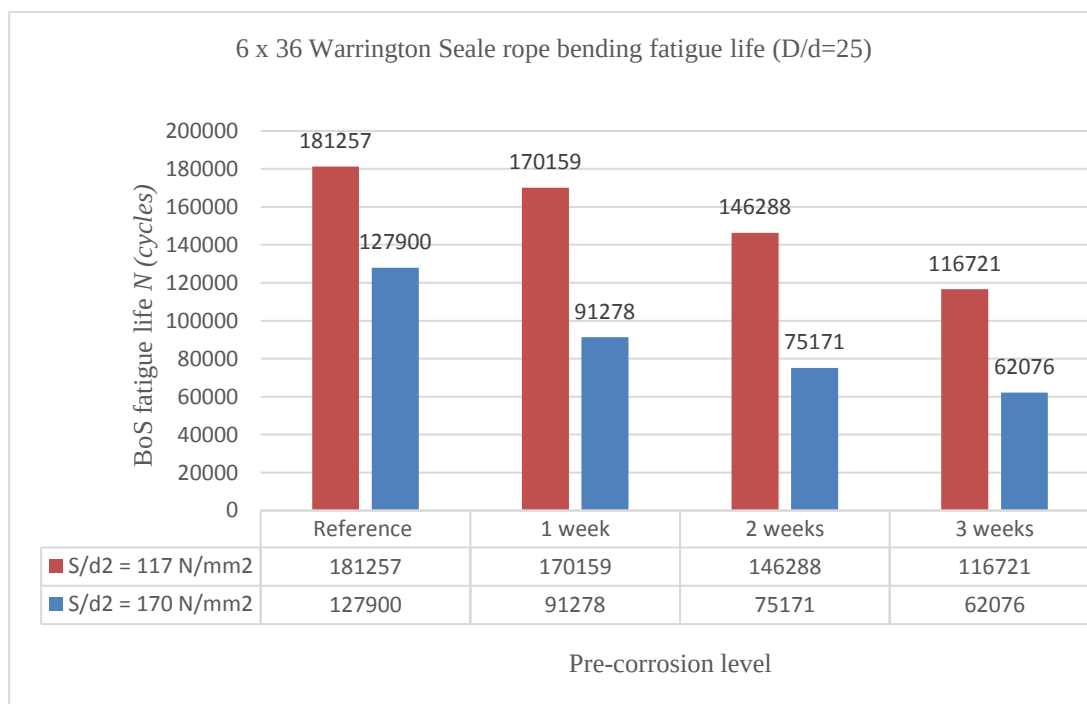


Figure 5.30 : 6 x 36 Warrington Seale rope BoS fatigue life with three different corrosion levels and different tensile load.

When 6 x 36 Warrington-Seale rope samples, that have been kept in corrosion cell for one, two, three weeks, tested with $S/d^2=170$ N/mm² and diameter ratio $D/d=25$, the bending fatigue lifetime reduces 28,64%, 41,23%, 51,46% respectively. On the other hand, when the specific tensile load decrease from 170 N/mm² to 117 N/mm² while all other parameters are the same, bending fatigue lifetime reduces 6,12%, 19,3%, and 35,6% respectively. According to these results, combine effects of tensile load and corrosion, the bending fatigue life of the wire rope reduces dramatically. It means wire rope exposed to corrosion effect is very sensitive to increase in tensile load.

Same tests repeated for 32 (W) x 7 Soliflex rotation resistant rope. Bending tests have been performed with the sheave 250 mm in diameter. Test results according to stated

parameters can be seen in Table 5.6. 32 (W) x 7 Soliflex rotation resistant rope is less sensitive to corrosion. 17.0 kN and 11.7 kN tensile load applied to the rope samples.

Table 5.6 : Effect of tensile load on pre-corroded 32 (W) x 7 Soliflex rotation resistant rope.

Test Number	Specific Tensile Load S/d^2 (N/mm ²)	Corrosion Level	Fatigue Life Endurance (N)	Reduction in Fatigue Life %
Test 5	170	Reference test	33140	-
Test 6	170	1 week	31920	-
Test 7	170	2 weeks	33368	-
Test 8	170	3 weeks	34628	-
Test 9	170	4 weeks	32258	-
Test 10	170	5 weeks	33464	-
Test 11	170	6 weeks	32156	-
Test 12	170	7 weeks	30465	-
Test 13	170	8 weeks	23852	28,02%
Test 14	170	9 weeks	17852	46,13%
Test 15	170	10 weeks	12476	62,35%
Test 16	170	11 weeks	9328	71,85%
Test 17	170	12 weeks	4498	86,40%
Test 26	117	Reference test	87880	-
Test 27	117	1 week	86978	-
Test 28	117	2 weeks	85976	-
Test 29	117	3 weeks	86526	-
Test 30	117	4 weeks	86762	-
Test 31	117	5 weeks	85354	-
Test 32	117	6 weeks	86206	-
Test 33	117	7 weeks	85888	-
Test 34	117	8 weeks	84358	-
Test 35	117	9 weeks	80322	8,60%
Test 36	117	10 weeks	72798	17,16%
Test 37	117	11 weeks	58112	33,87%
Test 38	117	12 weeks	46476	47,11%

When 32 (W) x 7 Soliflex rotation resistant rope samples, that have been kept in corrosion cell for one to twelve weeks, tested with $S/d^2=170$ N/mm² and diameter ratio $D/d=25$, the bending fatigue lifetime starts reducing after it has kept in corrosion cell eight weeks. Influence of corrosion until 8 weeks are not considerable e.g. results are in variation. If the 32 (W) x 7 soliflex rotation resistant rope sample keep in

corrosion cells for eight, nine, ten, eleven, and twelve weeks, BoS fatigue lifetime reduce 28.02%, 46,13%, 62,35%, 71,85%, and 86.4% respectively.

On the other hand, when the specific tensile load reduces from 170 N/mm² to 117 N/mm² while all other parameters are the same, bending fatigue lifetime start reducing after it has kept in corrosion cells 9 weeks. If the 32 (W) x 7 soliflex rotation resistant rope sample keep in corrosion cells for nine, ten, eleven, and twelve weeks, BoS fatigue lifetime reduce 8,60%, 17,16%, 33,87%, and 47,11 respectively. It can be concluded that, wire rope exposed to corrosion effect is very sensitive to increase in tensile load.

5.5.4 Effect of diameter ratio on pre-corroded wire rope

To examine the effect of sheave diameter, two different sheave used in the bending fatigue tests. One of them is 250 mm and the other 170 mm in diameter. This means diameter ratio D/d 25 and 17. Table 5.6 shows the test results which is conducted to 6 x 36 Warrington Seale wire rope wit 17.0 kN tensile load.

Table 5.7 : Effect of diameter ratio on pre-corroded 6 x 36 Warrington Seale rope.

Test number	Specific Tensile Load S/d^2 (N/mm ²)	Diameter ratio (D/d)	Corrosion level	Fatigue Life Endurance (N)	Reduction in Fatigue Life %
Test 1	170	25	Reference test	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 22	170	17	Reference test	77066	
Test 23	170	17	1 week	55222	28,34%
Test 24	170	17	2 weeks	48854	36,6 %
Test 25	170	17	3 weeks	39856	48,2 %

For this sample, it is observed when the diameter of sheave reduces from 250 mm to 170 mm, the bending lifetime of the 6 x 36 Warrington Seale rope reduces 39,7% as it expected (Feyrer, 2007). However, in this study combine effect of sheave diameter and corrosion were examined. In Figure 5.31 horizontal axis indicates the corrosion level and vertical axis indicates the bending life cycles. Red columns refer to the life cycles of the rope with sheave 250 mm in diameter while blue columns refer to life

cycles for sheave 170 mm in diameter. When 6 x 36 Warrington-Seale rope samples, that have been kept in corrosion cell for one, two, three weeks, tested with $S/d^2=170$ N/mm² and diameter ratio $D/d=25$, the bending fatigue lifetime reduces 28,64%, 41,23%, 51,46% respectively. On the other hand, when the sheave diameter decrease from 250 mm to 170 mm, while all other parameters are the same, the bending fatigue lifetime reduces 28,34%, 36,6%, and 48,2% respectively.

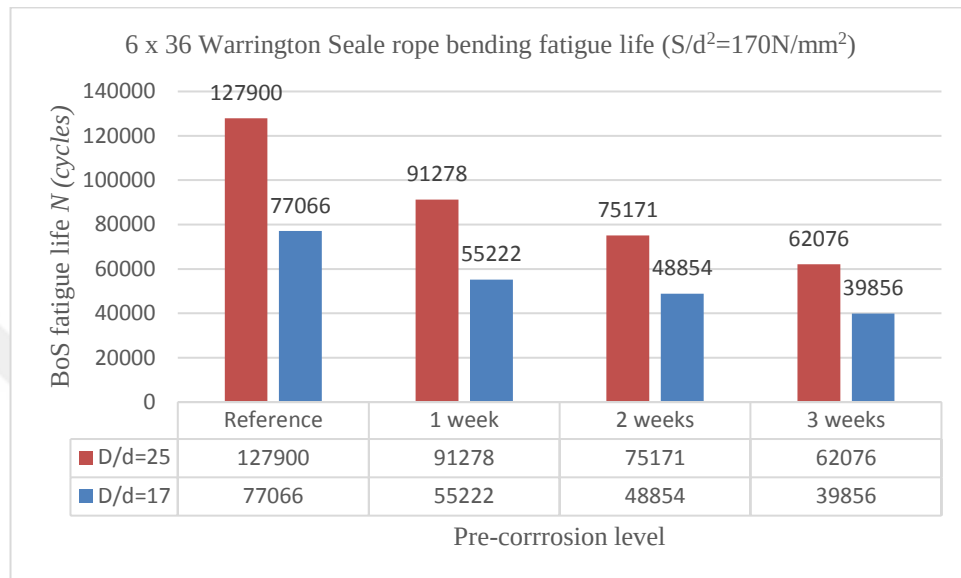


Figure 5.31 : 6 x 36 Warrington Seale rope BoS fatigue life with three different corrosion levels and with different sheave diameter.

According to test results, reduction in fatigue life with both sheave diameter, were almost same. It can be concluded that pre-corroded wire ropes are not very sensitive to the change in sheave diameter.



6. CONCLUSION

Corrosion effect on wire ropes are generally ignored in studies about wire rope under static or dynamic load in the literature. However, it cannot be ignored for the ropes are serving in corrosive environment. Many authors studied to investigate effective parameter on fatigue lifetime of the wire rope. The thing that makes this study unique, is combine effects of corrosion and fatigue on wire rope were examined. In order to accomplish this, several experiments with different parameters have been performed. The mayor parameter for this study was corrosion. Of course, when the corrosion level increase, the reduction on the lifetime of wire ropes are inevitably expected. Nevertheless, fatigue endurance is unpredictable, when corrosion and other parameters applied on same wire ropes. 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 this study, 6 x 36 Warrington Seale rope and 32 (W) x 7 Soliflex rotation resistant rope were studied for the BoS fatigue tests with different corrosion pattern. The obtained values indicated that corrosion diffusion time depending on wire rope composition. 32 (W) x 7 Soliflex rotation resistant rope has more layer than 6 x 36 Warrington Seale and it twisted more tightly. Therefore, it is harder to penetrate to inner wire in 32 (W) x 7 Soliflex wire rope, so it can be concluded that 6 x 36 WS rope is more sensitive to corrosive environment. There are various types of wire rope available in service and most of them are exposed to atmospheric influences. This work should be extended for different kinds of rope.

In addition to this, the effect of tensile load (S) was examined successfully for the BoS fatigue tests with different corrosion pattern. To accomplish this, 6 x 36 Warrington Seale wire rope used for the experiments. According to obtained results when the sheave 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 %. 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 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.

Lastly, the effect of diameter ratio (D/d) was examined for the BoS fatigue tests with different corrosion pattern. To accomplish this, 6 x 36 Warrington Seale wire rope used for the experiments. According to obtained results if the ratio D/d reduces from 25 to 17 the lifetime of the rope reduces the endurance of wire rope reduces 39.74 % (for $S=17.0$ kN). Experiments are performed on the wire ropes, which were kept in salty water for one to three weeks. 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.

As a conclusion, it can be said that the determining the appropriate rope composition is the most important parameter on fatigue lifetime of pre-corroded wire rope. Beside, it is possible to say that, tensile load is the other important parameter for the wire rope which will be used in the corrosive environment. In this study, bending fatigue life of wire rope were determined more accurately, by consideration of the aggressive application area of wire rope.

The experiment results is valid for specified rope compositions, tensile load and diameter ratio. There are various types of wire rope available in service and most of them are exposed to atmospheric influences, which causes corrosion and reduce lifetime of wire rope. Therefore, this study should be extended to different kind of ropes. Future works need to concentrated on the description of the relationship between corrosion level and wire rope composition. For more accurate results, future works need to conduct with new experimental setup which allows to examine corrosion and fatigue effects at the same time.

REFERENCES

- ASTM B117.** (2011). *Standard Practice for Operating Salt Spray (Fog) Apparatus*. American society for testing and materials.
- Begum, Z., Poonguzhali, A., Basu, R., Sudha, C., Shaikh, H., & Subba Rao, R. V.** (2011). Studies of the tensile and corrosion fatigue behaviour of austenitic stainless steels. *Corrosion Science*(53), 1424-1432.
- BS 6570.** (1986). The selection, care and maintenance of steel wire ropes. British Standard.
- Burns, J., Kim, S., & Gangloff, R.** (2010). Effect of corrosion severity on fatigue evolution in Al–Zn–Mg–Cu. *Corrosion Science*(52), 498-508.
- Chamos, A., Pantelakis, S., & Spiliadis, V.** (2010). Fatigue behaviour of bare and pre-corroded magnesium alloy AZ31. *Materials and Design*(31), 4130-4137.
- Chaplin, C. R., Ridge, I., & Zheng, J.** (1999). *Rope degradation and damage*. London: Health & Safety Executive, Offshore Technology Report,.
- Cookes Limited.** (2007). *Wire rope handbook*. Auckland, New Zealand.
- Cürgül, İ.** (1995). *Transport tekniği* (Vol. 1). Izmit: Kocaeli Üniversitesi Yayınları.
- Demirsoy, M.** (1991). *Transport teknigi-kaldırma makinalari* (Vol. 1). Istanbul: Birsen Yayınevi.
- DIN 15020-2.** (1974). Lifting Appliances; Principles Relating to Rope Drives: Supervision During Operation. Germany: Deutsches Institut für Normung.
- Ernst, H.** (1973). *Kaldırma makinalari*. Ankara: Fon Matbaası .
- Feyrer, K.** (2007). *Wire ropes: tension, endurance, reliability*. Springer Berlin Heidelberg New York.
- Giglio, M., & Manes, A.** (2003). Bending fatigue tests on a metallic wire rope for aircraft rescue hoists. *Journal of Engineering Failure Analysis*(10), 223-235.
- Gorbatov, E., Klekovkina, N., Saltuk, V., Vogel, V., Barsukov, V., Barsukov, E., Kurashov, D.** (2007). Steel rope with longer service life and improved quality. *Journal of Metallurgist*(51), 279-283.
- Gruenberg, K., Craig, B., Hillberry, B., Bucci, R., & Hinkle, A.** (2004). Predicting fatigue life of pre-corroded 2024-T3 aluminum. *International Journal of Fatigue*(24), 629-640.
- Jones, K., & Hoepfner, D. W.** (2005). Pit-to-crack transition in pre-corroded 7075-T6 aluminum alloy under cyclic loading. *Corrosion Science*(47), 2185-2198.
- Obert, B., Ngo, K., Hashemi, J., Ekwaro-Osire, S., & Sivam, T.** (2000). An investigation of the reduction in tensile strength and fatigue life of pre-corroded 7075-T6 aluminum alloy. *Journal of Materials Engineering and Performance*(9), 441-448.

- Onur, Y. A., & Imrak, C. E.** (2012). Experimental and theoretical investigation of bending over sheave fatigue life of stranded steel rope. *Indian Journal of Engineering and Materials Sciences*(19), 189-195.
- Onur, Y. A., & Imrak, C. E.** (2013). Experimental determination of degradation influence on bending over sheave fatigue life of steel wire rope. *Indian Journal of Engineering and Materials Sciences*(20), 14-20.
- Ridge, I., Chaplin, C., & Zheng, J.** (2000). Measurement of cyclic bending strains in steel wire rope. *Journal of Strain Analysis*(35), 545-558.
- Ridge, I., Chaplin, C., & Zheng, J.** (2001). Effect of degradation and impaired quality on wire rope bending over sheave fatigue endurance. *Journal of Engineering Failure Analysis*(8), 173-187.
- Salman, O.** (2010). Tasıyıcı halatların mekanik özelliklerinin incelenmesi. MSc Thesis. Istanbul Technical University.
- Schönherr, S.** (2005). Influence of the fleet angle on the service life of wire ropes running over sheaves. *PhD Thesis*. Stuttgart University.
- Southwest Wire Rope Inc.** (2008). *Technical Data Manual*. Houston, Texas.
- Sturgeon, W. C.** (1990). Elevator maintenance and traffic. *Elevator World Educational Package and Reference Library*(2), 42-45.
- Torkar, M., & Arzensek, B.** (2002). Failure of crane wire rope. *Journal of Engineering Failure Analysis*(9), 227-233.
- TS EN 12385-2.** (2005). Çelik tel halatlar- Güvenlik- Bölüm 2: Tarifler, Kısa gösteriliş ve sınıflandırma. Ankara: Türk Standartları Enstitüsü.
- TS ISO 4309.** (1999). Vinçler- Tel halatlar- Muayene ve hizmet dışı bırakma için uygulama kuralları. Ankara: Türk Standartları Enstitüsü.
- Turner, J., & Barnes, C.** (2002). Lubrication basics for wire ropes. *Machinery Lubrication Magazine*, 4.
- Union.** (2016). Wire rope user's handbook.
- Verreet, R.** (1998). *Calculating the service life of running steel wire ropes*. Kerkel, Germany: Casar Drahtseilwerk Saar GmbH Internal Report.
- Verreet, R.** (2002). *Steel wire ropes for cranes- problems and solutions*. Kerkel, Germany: Casar Drahtseilwerk Saar GmbH Internal Report.
- Verreet, R.** (2004). *Inspection of steel wire ropes*. Kerkel, Germany: Casar Drahtseilwerk Saar GmbH Internal Report.
- Verreet, R., & Lindsay, W.** (1996). *Wire rope inspection and examination*. Kerkel, Germany: Casar Drahtseilwerk Saar GmbH Internal Report.
- Verreet, R., & Ridge, I.** (2005). *Wire rope forensics*. Kerkel, Germany: Casar Drahtseilwerk Saar GmbH Internal Report.
- Yetiştiren, H., Zeren, A., & Feyzullahoğlu, E.** (2007). Tasıma tekniği ekipmanlarının bakımında kullanılan tahribatsız muayene yöntemleri. *Mühendis ve Makina*, 48(571), 17-24.

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- **Salman O.**, Bezzera K., Machado J., Carvalho V., Soares F., Leao C.P., 2015: Design of a Conceptual Bed Mattress for Reducing Pressure on Bony

Prominences, IMECE 2015, Proceedings of the 14th International Mechanical Engineering Congress & Exposition, November 13-19, 2015 Houston, Texas, USA.

- Altuntas M., **Salman O.**, Imrak C.E., 2014. Experimental Stress Analysis of Elevator Guiding Equipment , *Key Engineering Materials*, 572, 177-180.
- Erdonmez C., Imrak C.E., **Salman O.**, 2012: Complex Wire Rope Models For Lifts, ELEVCON, The 19th International Congress on Vertical Transportation Technologies, May 22-24, 2012 Miami, USA.
- Kayaoglu E., **Salman O.**, Candas A., 2011. Study on Stress and Deformation of an Elevator Safety Gear Brake Block Using Experimental and FEA Methods, *Advanced Materials Research*, 308(310), 1513-1518.
- Kayaoglu E., Gerdemeli I., **Salman O.**, 2011: Design for Assembly in Concurrent Engineering A Case Study on Its Application: Package Cutting Unit, IN-TECH 2011, International Conference on Innovative Technologies, September 01-03, 2011 Bratislava, Slovakia.
- Erdönmez C., **Salman O.**, Imrak C.E., 2010: Characterizing the Finite Element Analysis of Nested Helical Geometry and Test Procedure for Wire Ropes, ECCOMAS 2010, IV European Conference on Computational Mechanics – Solids, Structures and Coupled Problems in Engineering, May 16-21, 2010 Paris, France.
- Imrak C.E., **Salman O.**, 2009: An Application of Reverse Engineering in Concurrent Engineering, PIME'09 Theoretical and Experimental Problems of Materials Engineering Conference, August 24-27, 2009 Ostravice, Czech Republic.