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Causes of Failure of Steel Wire Rope – A Review

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***Abstract*: This article explores the possible causes of failures of steel wire ropes, especially in crane accidents. Wire ropes are specifically made to withstand heavy load and possess great tensile strength however, several factors might cause the failure of the wires to an irreversible extent. Strength of ropes as well as their application depends heavily upon their core; ropes with steel core are stronger and durable as compared to the ropes with fiber core. One of the main reasons of failure can be lack of standardization along with other factors. Fracture of strands lead to their breakage and ultimately collapse of the structures. This article compiled various studies conducted by forensic scientists to investigate the causes of failure of steel wire ropes that led to the collapse of machinery or structure. Based on their findings, this paper discussed the shortcomings of standardization of steel wire ropes.**

***Keywords*: Bureau of Indian Standards, core, corrosion, examination, failure, fatigue, fracture, steel wire ropes, strand, tensile strength.**

1. Introduction

Wire rope [1], just like any other rope, is made up of several strands of metal (ideally steel with fibers sometimes) twisted together to form a spiral type structure that possesses great tensile strength and other mechanical properties. Wire rope is infact more famous than we know and can be used for both domestic as well as engineering purpose. It's because of its unique strength and flexibility, thanks to the structure of the rope and tensile strength of steel, wire ropes are commonly used for construction purposes. Wire ropes were invented in 1834 but efficiently employed by Er. Wilhelm Albert [2] only by 1836. Before the introduction of wire ropes, coconut fibers were used for anchoring. Jute fibers were predominantly used for various purposes. There was one special type of fiber, obtained from the leaves of abaca, manila hemp, was also employed for engineering and construction purposes. Earlier accounts of wire ropes include the involvement of wrought iron chains for lifting & hoisting. This led to several accidents due to which these chains were replaced with strands of fibers twisted together to enhance their strength and replacing wrought iron core with steel due to its unique mechanical strength and properties. Modern wire ropes have core of stainless steel.

Steel wires can be of carbon steel material (bright), Zinc coated (galvanized), Drawn wires (coated with very thin layer of zinc just before it reaches its final dimension), Zinc-Aluminum coated wire and Stainless-steel wire (18% Cr and 8% Ni alloy).

2. Structure and Construction of Wire Rope

A. Core and Configuration

A typical rope wire consists of 3 parts [3]: A core made up of either fiber, metal or strand of metal; helically twisted strand of wires & wires.

Fiber core [4] is usually made up of manila hemp or jute fiber however cores made up of nylon and polyester are also preferred. Synthetic fiber cores are known for their durability.

Independent Wire Strand Core type consists of a core made up of strands of same metal as outside. Known for its higher rigidity and flexibility, IWSC type is widely used in automobiles and office uses.

Independent Wire Rope Core type consists of a metal wire in the center around which strands are twisted. In order to have durability, IWRC type wires are coated with nylon. Configuration of strands is what differentiates between IWRC and IWSC type rope. IWSC type usually contains a very simple type of configuration, say 7*7 type configuration will have 7 strands of wire around metal core containing 7 wires each. Similarly, a wire type 1*7 would contain 7 strands of wire around core with one wire each.

Configuration of IWRC is bit complicated. A configuration of {(9*9) + (1+17) *7}. A wire with this configuration would have 9 strands (including central core) each containing 9 wires in the core with 7 strands containing 17 wires each where 1 represents core part.

On a broader note, steel wire rope can be further classified as Warrington type, Fill type, Seale type and Warrington- Seale type. These are however, just profile of the strands like how they're arranged.

B. Characteristics of an Ideal Rope Wire [5]

- *Strength of the rope:* Maximum force it can carry- this property is core and most important property taken into consideration while constructing a rope wire. Strength includes both tensile and elastic strength. Strength criteria is defined in BIS according to the type, configuration and weight of the rope manufactured. Every wire manufactured should follow the standard guidelines by BIS only. Ideally, when tested, a rope should break at the force equal or more than the minimum force required to break off.
- *Resistant to fatigue:* Rope wires need to be resistant to bending and other kind of deformations caused due to

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regular friction or wear and others. These deformations ultimately led to fatigue and breakage of wires therefore a rope must have this property to become more durable. An ideal wire should never bend, especially around sheaves or drums. This bending stress can eventually reduce the strength of the rope and cause fatigue & failure.

- *Resistant to external forces:* External force or high pressure can distort the cross section of a rope thus crushing it and causing severe damages. This might lead to serious life-threatening accidents or failures of mechanisms. A rope crushed cannot operate, move or adjust properly.
- *Wear or erosion resistant:* A rope wire should be made in such a way that it can resist constant wear and tear or erosion of the outer layer of the rope. Outer surface is usually abrased over time due to regular application of external forces or pressure. 'Peening' deformation is one of the most common types of deformation of the wires that causes fatigue in later stages.
- *Anti-rotation:* Whenever a rope is being loaded, a torque is induced within the strands that might cause unbending of the rope. However, a rope is supposed to work with this torque only. In some cases, this torque can cause load to rotate and ultimately breakage of strand. Thus, ropes should be rotation resistant to avoid accidents.

Though these properties are desirable, not every rope can possess all of them, but they can be manufactured in a way to possess at least 2 of these properties.

Table 1
Standardization of rope wires based on their core

IS Standard	Core Material	Function
IS 1855:2005	Fiber or steel	Haulage, winding
IS 1856:2005	Soft jute	Haulage
IS 2266:2002	Flattened/oval core	Cranes/ Other engineering functions
IS 2365:1977	Only fiber	Escalator/lift/hoists
IS 2581:2002	Both	Cargo gearing, anchoring etc.
IS 2762:1982	Higher stnd.	Slings
IS 13156:1991	Higher stnd.	Sheeve pully

3. Types of Wire Ropes

A. Standardized as per Bureau of Indian Standards [6]

Wire ropes can be divided into 7 categories on the basis of their load carrying capacity or in layman term, their function, as per IS. Standards set up by BIS are based on the diameter, core type, configuration, construction, mass and maximum force it can endure before breaking off. Some of the most common wire ropes are constructed are of 1570, 1770 and 1960 grade. Every wire constructed should fulfil the above criteria as per these grades. Another grade of wire employed is 1420 however it is only used for multi-rotational wire strand.

B. Based on Twisting of Strands

There are usually 4 types of twists found in rope wires: ZS (right cross), ZZ (Right parallel), SC (left cross), SS (Left parallel).

There are 2 types of lay or twist encountered in wire ropes: Regular type and Lang type. Basically, in regular twist, strand and wires are twisted in opposite direction and parallel to each other whereas in lang type, both wires and strand are in the same direction and often known as cross twist.

4. Protection and Galvanization

Wires are coated with nylon or ultra-thin Polytetrafluorethylene resin (around 7 microns) that replaced nylon (around 20 microns) in thickness. PVC can also be used to protect galvanized steel wire ropes from erosion and corrosion. Talking about galvanization, steel wires are coated with zinc as per the specifications mentioned in IS 1835. In short, from construction to its polishing, steel wire ropes should be made as per BIS.

5. Types of Damage Encountered

A. Mechanism [7]

Before discussing the damages to the ropes, cause and mechanism of failures should be known. Two things are taken into consideration while constructing a wire rope: Its tensile strength i.e., maximum force that a rope might bear until it breaks off & load capacity or WLL i.e., maximum weight that a rope can carry before breaking off. This factor takes everything into consideration; friction, age, knots, temperature differences, abrasions, twisting etc.

Any wire can be damaged [8] if the load or force surpasses the set standard. Damages can also be caused due to corrosion, erosion or simply aging of the wire i.e., wire is too old and needed to be replaced. Study of various damages and their correlation was completed by few researchers on real rope sample recovered from many accident sites [cable car accident (December 29, 2010); cage hoist accident in mining site (march 9, 2017)]. These damages might result in fracture of rope strands, thus failure of the machine.

B. Types

- *Fatigue:* When a wire is twisted, used, knotted, stretched beyond its bearable limits, it undergoes fatigue. Fatigue can happen to both internal as well as external strand of a wire and can be the leading cause of wire and strand fracture. Fatigue might also cause scraping of strands.
- *Distortion:* Any alteration of the wire from its original form, including irreversible twisting or bending of the wire, cracks or fractures, loosening or relaxation of wire or flattened strand or a portion of wire. These deformations might be the result of an impact of any particular portion of the rope.
- *Rust:* Corrosion of wire ropes is a common phenomenon, caused due to oxidation of the outer surface of the wire. Well, these days galvanized ropes are preferred moreover ropes made up of stainless steel are resistant to corrosion. Zn-Al alloy galvanized wires are also effective against corrosion due to the combined rust-inhibition properties of Al and Zn and

far better than only Zn coated wire ropes.

- *Wear and tear of ropes [9]:* A phenomenon common to every single substance, eventual degradation of any product due to its prolonged use. Similar to other products such as tires which are provided with a TWI and need to be replaced after wear reaches a certain limit, ropes are also replaced when they are aged or attenuated. Wear and tear, often referred to as erosion of rope can be minor too extreme to an extent that it might cause accidents and catastrophic failures (discussed below). Erosion ultimately reduces the WLL, tensile strength and elasticity of rope.
- *Wire & Strand fracture:* Above factors contribute to the fracture of either wire(s) or strand; strand breakage results in serious accidents and catastrophic failures.
- We can conclude that erosion, corrosion, deformation and fatigue can cause serious wire damages or fractures whereas combining effects of every factor can result in fracture of whole strand and ultimately rope itself.

6. Investigation and Causes of Wire Rope Failures in Case of Crane Accidents

A. Investigation

Usually, crane accidents involve hoist wire failure or breakage, as in the case of Gulf of Mexico [10] accident. A crane, in 1998 was lifting a module of Petronius platform when its hoist wire suddenly snapped. Module fell in the Gulf, killing more than 60 people and injuring almost 65 people.

A similar accident happened when a crawler crane [11] was lifting a steel plate, weighed almost 2T, its wire snapped when the plate was 1 m in the air. This led to collapse of crane boom on nearby factory.

Surprisingly the crane was serviced just few months ago and its hoist wire was replaced just 5 months before the accident. Location of fracture of rope and complete configuration of the crane was analyzed during the investigation process.

Examination of the rope was preferably conducted on and around the area of fracture through various methods such as visual analysis, SEM analysis, analysis of corrosion and erosion around the fractured fragments and EDX.

After the intensive investigation, following observations were drawn:

i. Fractured fragments were all corroded near the breakage points
ii. Microscopic examination indicated the presence of fatigue due to rust i.e., the main reason of the breakage was rusting & fatigue.
iii. There were signs of wear & tear of the edges.

Based on the above observations, it was concluded that:

i. If proper maintenance was conducted then the corrosion and fatigue might have been noticed earlier.
ii. Oiling was not done properly.
iii. Improper and uneven greasing of hoist rope caused severe corrosion of some parts of the rope due to chemical reactions and marine exposure.
iv. Poor inspection and maintenance.

B. Examination and Detection of Failures

Failure analysis of rope wires [12] is carried out to determine main cause of the accident, or whether it was accident or deliberated act. When analysis is done to determine the cause of fracture, it is known as fractographic analysis of wire strand. Though there are various techniques but following discussed methods are most commonly employed while investigating the cause of crane failures.

Prior to any examination, collection and preservation of broken or damaged or even suspected rope sample is crucial step. Followings things should be taken into considerations:

a. Survey the scene of accident; know the configuration of crane.
b. Locate the site of fracture.
c. Photograph the site of breakage using a digital camera.
d. Collect the fragment and send it to the laboratory for analysis.

Most of the analysis methods used for failure analysis are non-destructive in nature.

1) Physical examination

Sample is examined visually or physically for its type and basic information. This examination is also known as macroscopic examination of rope wires. Following measurements and features are documented in this analysis:

1. Diameter of the rope using vernier calipers
2. Type of wire i.e., whether it is of Fiber core type, IWSC type or IWRC type.
3. Type of lay or twist in the rope
4. BIS standards and whether this rope was upto that standard
5. Configuration of the strands (7*19, 6*19 etc.)
6. Preliminary analysis of fractured area and ropes around that area with the help of digital photographs and sample itself.

2) Microscopic examination

Microscopic examination of rope wires is referred to as metallurgical or metallographic analysis. Microscopic analysis is conducted to examine cross-sectional and transverse area of the wire basically to determine cause of fracture. Often fatigue and deformation is analyzed with the help of optical microscope. Conclusions are made on the basis of optical metallographs.

3) SEM study

Sometimes, microscopic examination fails to detect the sign of fatigue or any other deformations near the edges or at the site of fracture. In that scenario scanning electron microscope is used for in depth analysis. Various parameters such as origin point of fracture, striation marks, breech face marks, corroded area, type & pattern of fractures (e.g., cup & cone type), fracture fingerprinting, morphological studies, elemental analysis etc. are examined. This kind of examination is known as fractographic analysis and is used to determine and confirm the root cause of accident as well as if the wire was made as per the set standards or not through its elemental analysis.

There was a minor crane accident that occurred on November

2013. The rope was constructed in a manner to have a maximum work load of 261kN. A detailed analysis was carried out as a part of research by investigators and researchers.

7. Choosing the Best Ropes [13]

So far, we have discussed the types of ropes and their characteristics based on their abilities to resist deformations, but not every rope can have all the qualities. As already mentioned above, a rope can have combination or 2 or more features but not all.

e.g., If a rope is supposed to be fatigue free, it should have more and smaller wires on its outer surface. But this would make it vulnerable to deformations and abrasions. if manufactured otherwise, it would require to have lesser but larger wires on its outer surface that would make it vulnerable to fatigue. It's never both.

Therefore, of all the qualities mentioned above a rope chosen should be galvanized, have more tensile strength and should be a perfect balance of fatigue and abrasion resistance. Since it cannot be free from any of the deformations, ropes should be inspected regularly and replaced on suspicion of potential erosion or corrosion.

Best way to choose perfect rope wires is the standard set up by BIS i.e., no wire should be made outside the given stds. As already discussed above, every strand, type and configuration have a set of mass and load capacity. Remember not to overweight the wires i.e., a rope should always carry burden less than given minimum mass it can withhold before breaking off.

8. Discussion and Conclusion

Investigation of structural and machinery failure is not an easy task to achieve; it is not an easy task to establish the occurrence to a particular cause. In case of structural failures, analysis of construction materials might relate the collapse to lack of standardization. Similarly, analysis of wire ropes, as in case of elevator and crane accidents can establish the possible cause of accident [14].

Similarly, rope wires are also installed in various artefacts such as buildings or over bridges where there are higher chances of their failure.

Factors such as wear and tear, fatigue and corrosion are indicative of human negligence and lack of monitoring. On the other hand, premature breakage especially when ropes were properly standardized and taken care of indicates the possibility of something more than just accident.

Even single fracture in one of the strands can lead to the collapse of whole rope and ultimately the structure. In case of crane accidents however, this collapse may or may not cause any damage to humans whatsoever but when elevator rope collapses, the damage causes are beyond imaginable.

Wire fractures should be inspected regularly to avoid the catastrophe from being happening. Either way, no wire rope should be made outside of the standards specified by BIS for certain type, however few modifications such as introduction of plastic layer, changes in diameter, introducing rotation and corrosion resistance, galvanization or anything that can increase the load bearing capacity of the rope can be introduced by the manufactures accordingly.

There are so many aspects of failure or rope wires but major concern is fatigue and corrosion that leads to fracture followed by strand breakage of the rope as a whole.

So far, stainless steel wires are preferably used due to their high tensile strength, better elasticity and low chances of erosion even without galvanization.

There are various non-destructive techniques [15] for the analysis of rope wires as well such as acoustic emission technique, ultrasound guided wire technique, eddy current method etc. but all of these methods are currently being studied and there are lot of shortcomings with the result of these methods.

With the improvement in forensic engineering and instrumentation, it would become easier to detect damages in the wires at early stages in near future and hopefully these unfortunate accidents might be avoided.

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